DOCTORAL THESIS

UCAM
UNIVERSIDAD CATÓLICA
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INTERNATIONAL DOCTORAL SCHOOL

Doctoral Programme in Health Sciences

Evaluation of dental hygiene prophylaxis systems on dental implants: randomized clinical trial of changes in oral health status

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Carolina Maiorani

Supervisors:

Prof. Dr. Carlos Pérez-Albacete Martínez

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THESIS SUPERVISORS’ AUTHORISATION FOR THESIS SUBMISSION

Prof. Andrea Scribante and Prof. Carlos Pérez-Albacete Martínez, as Supervisors of the Doctoral Thesis ‘Evaluation of dental hygiene prophylaxis systems on dental implants: randomized clinical trial of changes in oral health status’ by Ms Carolina Maiorani in the Doctorate Programme Health Sciences, **authorise its submission**, given that it meets the required conditions for its defence.

Which I hereby sign in compliance with Spanish Royal Decree 99/2011, of 28 January, in Murcia, on 27 September, 2025.

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ABSTRACT

This randomized clinical trial investigated the effectiveness of two professional biofilm decontamination protocols in the long-term maintenance of peri-implant health. The two approaches compared were erythritol-based air polishing and ultrasonic instrumentation with PEEK-coated tips. A total of 120 patients with at least one implant-supported crown—restored with feldspathic ceramic, zirconia, or lithium disilicate—were recruited and randomly assigned to one of the two treatment groups. Clinical parameters including probing pocket depth (PPD), bleeding on probing (BoP), and plaque index (PI) were recorded at baseline and at 6, 12, 18, and 24 months. Patients were also stratified according to the type of prosthetic crown, forming six distinct subgroups.

The results demonstrated that both treatment protocols led to statistically significant improvements in all clinical parameters over the 24-month follow-up period. However, patients treated with erythritol-based air polishing exhibited a more rapid and consistent reduction in PPD, BoP, and PI, achieving complete plaque control and absence of bleeding sites earlier than those treated with ultrasonic debridement. No significant differences were observed between subgroups based on crown material, suggesting that the effectiveness of both interventions was independent of the prosthetic material used.

In conclusion, while both methods proved effective in maintaining peri-implant tissue health, erythritol-based air polishing emerged as the more efficient and clinically advantageous option. Its superior ability to control inflammation and biofilm accumulation supports its recommendation as a preferred strategy for long-term peri-implant maintenance.

KEY WORDS

Peri-implant maintenance; erythritol air polishing; ultrasonic instrumentation; PEEK tip; biofilm control; probing pocket depth; bleeding on probing; plaque index; implant-supported prostheses; restorative materials.

RESUMEN

Este ensayo clínico aleatorizado investigó la eficacia de dos protocolos profesionales de descontaminación del biofilm en el mantenimiento a largo plazo de la salud periimplantaria. Los dos enfoques comparados fueron el pulido con airflow a base de eritritol y la instrumentación ultrasónica con puntas recubiertas de PEEK. Se reclutaron un total de 120 pacientes con al menos una corona soportada por implante —restaurada con cerámica feldespática, zirconia o disilicato de litio— y se asignaron aleatoriamente a uno de los dos grupos de tratamiento. Se registraron parámetros clínicos, incluyendo la profundidad al sondaje (PPD), el sangrado al sondaje (BoP) y el índice de placa (PI), al inicio del estudio y a los 6, 12, 18 y 24 meses. Además, los pacientes se estratificaron según el tipo de corona protésica, formando seis subgrupos distintos.

Los resultados demostraron que ambos protocolos de tratamiento condujeron a mejoras estadísticamente significativas en todos los parámetros clínicos durante el periodo de seguimiento de 24 meses. Sin embargo, los pacientes tratados con pulido con airflow a base de eritritol mostraron una reducción más rápida y constante en PPD, BoP y PI, logrando un control completo de la placa y ausencia de sitios con sangrado antes que aquellos tratados con desbridamiento ultrasónico. No se observaron diferencias significativas entre los subgrupos según el material de la corona, lo que sugiere que la eficacia de ambas intervenciones fue independiente del material protésico utilizado.

En conclusión, aunque ambos métodos demostraron ser eficaces en el mantenimiento de la salud de los tejidos periimplantarios, el pulido con airflow a base de eritritol se destacó como la opción más eficiente y ventajosa desde el punto de vista clínico. Su superior capacidad para controlar la inflamación y la acumulación de biofilm respalda su recomendación como estrategia preferente para el mantenimiento periimplantario a largo plazo.

PALABRAS CLAVES

Mantenimiento periimplantario; airflow a base de eritritol; instrumentación ultrasónica; punta de PEEK; control del biofilm; profundidad al sondaje; sangrado al sondaje; índice de placa; prótesis soportadas por implantes; materiales restauradores.

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At the end of this challenging and fulfilling journey, I would like to express my heartfelt gratitude to all the professors of Universidad Católica San Antonio and the University of Pavia. Their academic guidance, constant encouragement, and human support have not only helped me achieve the goals of this doctoral project but have also enriched my understanding of research methodology and shaped my future in academia.

I am deeply thankful to my family—especially my mother, my sister, and my beloved niece, who was born during the final stage of this journey. Her arrival brought unexpected light, renewed strength, and a sense of perspective that helped me face the most intense moments with hope and joy. She has already taught me how something so small can carry infinite meaning.

To those who are no longer here but continue to guide me from above, I dedicate a special thought. Their presence, though invisible, has been felt every step of the way.

A warm thank you goes to my mentor, Andrea, for believing in me, for challenging me, and for being a constant source of inspiration—his example has greatly shaped both my academic and personal growth.

QUOTE

‘And once the storm is over, you won’t remember how you
made it through, how you managed to survive. You won’t even
be sure, whether the storm is really over. But one thing is
certain. When you come out of the storm, you won’t be the same
person who walked in. That’s what the storm is all about’.
Haruki Murakami, Kafka on the Shore (2002).

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ACRONYMS AND ABBREVIATIONS

aPDT, antimicrobial Photodynamic Therapy

BoP, Bleeding on Probing

CER, Feldspathic Ceramic

DISIL, Lithium Disilicate

EAP, Erythritol-based Air-Polishing

EFP, European Federation of Periodontology

e.g., exempli gratia (Latin for "for example")

EMS, Electro Medical Systems (Nyon, Switzerland)

Er:YAG, Erbium:Yttrium-Aliminum-Garnet

Max, Maximum

Mdn, Median

Min, Minimum

µm, micrometer (one millionth of a meter; 1 µm = 10^{-6} m)

mm, millimeters (unit of length equal to one thousandth of a meter)

n, number of subjects

ns, not significant (used to indicate a result that is not statistically significant)

p, p-value (probability value used in statistical hypothesis testing)

PCT, Peri-implant Connective Tissue

PEEK, Polyether Ether Ketone

PI, Plaque Index

PIE, Peri-implant Epithelium

Rank Sum Diff, Rank Sum Difference (difference in rank sums used in non-parametric statistical test)

S3, Evidence and consensus- based clinical practice guidelines (highest level in the German AWMF classification)

SD, Standard Deviation

ssp, species pluralis; used to refer to multiple species within a genus

T, Timepoints of clinical evaluation: baseline (T0), and follow-up visits at 6 (T1), 12 (T2), 18 (T3) and 24 months (T4)

UNC 12, University of North Carolina periodontal probe with millimetre markings up to 12 mm

UPI, Ultrasonic Instrumentation with PEEK Tip

vs, versus

ZIR, Zirconia

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I – INTRODUCTION

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1.1. ANATOMY AND HISTOLOGY OF PERI-IMPLANT TISSUES

Implant-supported prosthetic rehabilitation has become a well-established therapeutic solution for the replacement of missing teeth in a variety of clinical scenarios. Dental implants are biomedical devices made of biocompatible materials that are surgically inserted into the alveolar bone, residing either entirely or partially beneath the epithelial surface [Von Wilmowsky C et al., 2013]. The surgical protocol involves creating an osteotomy to facilitate the correct positioning and primary stabilization of the implant fixture [Von Wilmowsky C et al., 2013; Kligman S et al., 2021].

Following surgical placement, epithelial cells at the wound margins rapidly adhere to the implant surface, promoting the formation of a basal lamina and hemidesmosomal structures. This biological process leads to the establishment of an epithelial seal, functionally analogous to the junctional epithelium surrounding natural teeth [Lindhe J et al., 1998; Ivanovski S et al., 2018]. The maintenance of this epithelial barrier is essential for protecting peri-implant tissues from microbial invasion and for ensuring the long-term preservation of osseointegration [Bianchini MA et al., 2024].

Histologically, the peri-implant mucosa consists of an outer layer of keratinized oral epithelium, continuous with a sulcular epithelium that lines the peri-implant sulcus, mimicking the structural organization seen around natural teeth [Ivanovski S et al., 2018; Baus-Domínguez M et al., 2024]. However, several fundamental anatomical differences distinguish peri-implant tissues from their periodontal counterparts. Implants lack periodontal ligament fibers, cementum, neurovascular structures, and the periodontal vascular plexus. As a result, collagen fibers in peri-implant connective tissue are oriented parallel to the implant or abutment surface rather than inserting perpendicularly into the root cementum as they do in natural teeth [Berglundh T et al., 1991; Covani U et al., 2023].

The peri-implant connective tissue is characterized by dense collagen bundles originating from the periosteum of the alveolar crest, a reduced density of fibroblasts, and diminished vascularization, giving it a histological appearance akin to scar tissue [Meyer G et al., 2012; Tomasi C et al., 2016; Ivanovski S et al., 2018]. This composition, being less dynamic and less vascularized than natural periodontal tissues, results in increased susceptibility of peri-implant tissues to mechanical and microbial insults. Moreover, the absence of periodontal ligament structures entails the loss of proprioceptive feedback mechanisms. Unlike natural teeth, which are linked to the central nervous system through the periodontal ligament, dental implants lack the capacity to detect occlusal overloads. This deficiency increases their vulnerability to mechanical trauma, which can contribute to the initiation and progression of peri-implant tissue inflammation and marginal bone loss [Meyer G et al., 2012; Berzaghi A et al., 2025].

From a microbiological perspective, healthy peri-implant sites are predominantly colonized by oral streptococci, representing 45% to 86% of the supra- and subgingival microbiota, along with species such as *Actinomyces naeslundii, Actinomyces oris, Actinomyces meyeri, Neisseria ssp., and Rothia ssp* [Pokrowiecki R et al., 2017; de Campos Kajimoto N et al., 2024]. However, even clinically healthy peri-implant sulci may occasionally harbor periodontopathogens such as *Fusobacterium nucleatum, Prevotella intermedia, Porphyromonas gingivalis, and Aggregatibacter actinomycetemcomitans* [Pokrowiecki R et al., 2017; de Campos Kajimoto N et al., 2024; Herrera D et al., 2023]. The presence of these microorganisms alone does not necessarily lead to disease; rather, peri-implant infections are more closely associated with alterations in the host immune response and dysbiosis within the local microbiota [Renvert S et al., 2015; Di Spirito F et al., 2024].

The transition from peri-implant health to disease is characterized by significant alterations in the biofilm composition, including an increased prevalence of cocci, bacilli, and spirochetes, especially within the subgingival environment. Peri-implant mucositis typically involves a proliferation of bacteria from the orange complex, such as *Fusobacterium nucleatum, Prevotella intermedia,* and *Eubacterium ssp.,* along with a reduction in beneficial species like *Streptococcus spp.* and *Actinomyces spp.* As inflammation progresses to peri-implantitis, pathogens from both the orange and red complexes dominate, with *Porphyromonas gingivalis* and *Tannerella forsythia* representing the most prevalent species [Pokrowiecki R et al., 2017; de Campos Kajimoto N et al., 2024; Herrera D et al., 2023; Renvert S et al. 2015; Di Spirito F et al., 2024].

In addition to bacterial factors, mechanical stability plays a critical role in the successful integration of implants. When micromovements at the implant–bone interface exceeds the critical threshold of 50–150 µm during the early healing phase, osseointegration may fail, resulting in the formation of a fibrous encapsulation around the implant instead of direct bone contact [Meyer G et al., 2012; Kligman S et al., 2021]. Histologically, this fibrous tissue is less organized and poorly vascularized compared to healthy bone, undermining the mechanical stability and long-term success of the implant. These findings underscore the necessity of achieving optimal primary stability at the time of implant placement [Bianchini MA et al., 2024; Kligman S et al., 2021].

Recent studies have also emphasized the importance of soft tissue dimensions in maintaining peri-implant health. An adequate width of keratinized mucosa (≥2 mm) and sufficient mucosal thickness (≥2 mm) significantly enhance the establishment of a stable biological seal at the mucosa–implant interface, thereby reducing the risk of bacterial invasion and marginal bone loss. Conversely, thin peri-implant mucosal phenotypes are associated with a higher susceptibility to soft tissue recession and early crestal bone resorption [Ríos-Osorio N et al., 2025].

Histologically, the peri-implant epithelium (PIE) presents a structure similar to that of the natural junctional epithelium but is longer, non-keratinized, and structurally weaker. The underlying peri-implant connective tissue (PCT) is characterized by collagen fibers running parallel to the implant surface without direct attachment, combined with a reduced vascular network—factors that contribute to the scar-like morphology typical of peri-implant soft tissues [Ríos-Osorio N et al., 2025]. Furthermore, the supracrestal tissue attachment surrounding implants is generally wider (approximately 3–4 mm) compared to those around natural teeth. Although this adaptation may contribute to the mechanical stability of the mucosal seal, it does not entirely replicate the protective and regenerative properties of periodontal tissues. As a result, peri-implant tissues remain inherently more vulnerable to inflammatory diseases, highlighting the need for meticulous preventive and maintenance strategies to ensure the long-term success of implant therapy [Berglundh T et al., 1991; Ríos-Osorio N et al., 2025]. These anatomical and histological features, while allowing functional integration of implants, also contribute to the biological vulnerability of peri-implant tissues, predisposing them to inflammatory and degenerative changes [Assery NM et al., 2023].

1.2. BIOLOGICAL CHANGES IN PERI-IMPLANT TISSUES: FROM HEALTH TO DISEASE

The maintenance of peri-implant health is fundamental for the long-term success of implant-supported rehabilitations [Berglundh T et al., 2018]. Peri-implant health is defined clinically by the absence of signs of soft tissue inflammation, such as erythema, swelling, and suppuration, and by the absence of bleeding on gentle probing [Renvert S et al., 2018]. Probing depths may vary depending on implant design and soft tissue characteristics, and therefore increased probing depth alone does not necessarily indicate disease [Renvert S et al., 2018]. A key feature of peri-implant health is the stability of the marginal bone level following the initial post-surgical remodeling phase [Berglundh T et al., 2018].

Peri-implant mucositis represents the earliest stage of pathological change and is defined as an inflammatory lesion confined to the mucosa surrounding a dental implant without clinical or radiographic signs of supporting bone loss beyond the initial remodeling [Berglundh T et al., 2018; Renvert S et al., 2018; Figuero E et al., 2014]. Clinically, mucositis is diagnosed by the presence of bleeding on probing (BoP) and/or suppuration, often associated with redness and swelling. Histologically, peri-implant mucositis is characterized by an inflammatory infiltrate composed predominantly of neutrophils and lymphocytes within the connective tissue, with increased vascular permeability and epithelial ulcerations [Kormas I et al., 2020].

The development of peri-implant mucositis is primarily triggered by the accumulation of bacterial biofilms on the implant surface, eliciting a localized inflammatory response from the host [Figuero E et al., 2014]. If left untreated, mucositis may progress to peri-implantitis, an irreversible pathological condition characterized by both inflammation of the peri-implant mucosa and loss of the supporting bone structure [Berglundh T et al., 2018; Figuero E et al., 2014].

Peri-implantitis is diagnosed based on the presence of bleeding and/or suppuration on probing, increasing probing depths compared to previous examinations, and radiographic evidence of progressive crestal bone loss [Renvert S et al., 2018]. In cases where no previous clinical or radiographic data are available, peri-implantitis is assumed when probing depths are ≥6 mm in conjunction with BoP and bone loss ≥3 mm apical to the most coronal part of the implant body [Renvert S et al., 2018]. Histologically, peri-implantitis lesions display a dense inflammatory infiltrate extending deep into the connective tissues, associated with osteoclastic bone resorption [Kormas I et al., 2020].

Microbiologically, peri-implantitis lesions are dominated by complex multispecies biofilms, with Gram-negative anaerobic bacteria such as *Porphyromonas gingivalis, Tannerella forsythia, Fusobacterium nucleatum*, and *Treponema denticola* being particularly prevalent [Kormas et al., 2020; Heitz-Mayfield LJA et al., 2024]. Compared to periodontal pockets, peri-implant biofilms tend to be more diverse, possibly due to differences in surface topography and the absence of a periodontal ligament [Heitz-Mayfield LJA et al., 2024].

Epidemiological studies have revealed a wide variability in the prevalence of peri-implant diseases, reflecting differences in study populations, diagnostic criteria, and evaluation methodologies. According to Wada et al. (2021), peri-implant mucositis affects between 23.9% and 88% of patients and between 9.7% and 81% of implants, whereas peri-implantitis affects between 8.9% and 45% of patients and between 4.8% and 23% of implants [Wada M et al., 2021]. A systematic review by Roccuzzo A et al. (2021) estimated the weighted mean prevalence of peri-implant mucositis at 43% and peri-implantitis at 22% [Roccuzzo A et al., 2021]. More recently, a multicenter study by Apaza-Bedoya K et al. (2024) found peri-implant mucositis in 49.5% of patients and peri-implantitis in 15.15% of patients [Apaza-Bedoya K et al., 2024].

It is important to distinguish between prevalence rates expressed per patient and per implant. Prevalence per patient refers to the proportion of individuals affected by the disease, whereas prevalence per implant refers to the proportion of affected implants among all implants evaluated. This distinction is crucial for understanding the clinical burden and for interpreting epidemiological data correctly.

Several risk factors have been consistently associated with the development and progression of peri-implant diseases. Poor plaque control and inadequate oral hygiene remain the primary modifiable risk factors [Figuero E et al., 2014; Wada M et al., 2021; Apaza-Bedoya K et al., 2024]. A history of periodontitis has been identified as a strong predictor of peri-implant tissue breakdown [Berglundh T et al., 2018; Roccuzzo A et al., 2021]. Smoking, particularly heavy smoking, significantly increases the risk of peri-implantitis [Heitz-Mayfield LJA et al., 2024]. Other factors such as uncontrolled diabetes mellitus and systemic conditions like osteoporosis may contribute to disease susceptibility [Wada M et al., 2021; Apaza-Bedoya K et al., 2024]. Additionally, the presence of residual cement, inadequate implant positioning, and biomechanical overload have been implicated in disease initiation and progression [Heitz-Mayfield LJA et al., 2024; Figuero E et al., 2014].

Understanding the biological changes leading from peri-implant health to mucositis and ultimately to peri-implantitis highlights the critical importance of preventive strategies. Patient education, effective plaque control, smoking cessation programs, metabolic disease management, and professional maintenance care are essential measures aimed at preserving peri-implant health and ensuring the longevity of implant-supported rehabilitations [Berglundh T et al., 2018; Heitz-Mayfield LJA et al., 2024]. Early detection and treatment of peri-implant mucositis offer the best opportunity to prevent the irreversible tissue destruction associated with peri-implantitis.

1.3. BIOFILM CONTROL AND MAINTENANCE OF PERI-IMPLANT HEALTH

Preventing inflammation around dental implants is essential to ensure their long-term survival and functional success, as well as to safeguard the overall systemic health of the patient. Numerous clinical studies have emphasized that a targeted preventive approach, integrating both professional interventions and effective daily oral hygiene practices, significantly reduces the incidence of peri-implant mucositis and peri-implantitis [Herrera D et al., 2023; Jepsen S et al., 2015].

Bacterial biofilms are structured microbial communities that adhere to implant surfaces and play a critical role in the pathogenesis of peri-implant diseases. These biofilms, embedded in a self-produced extracellular polymeric matrix, protect the microorganisms from external insults and make mechanical removal challenging [Berglundh T et al., 2018; Renvert S et al., 2018]. In healthy peri-implant sites, the microbial composition is primarily dominated by Gram-positive facultative species, such as *Streptococcus spp.* and *Actinomyces spp*. However, when homeostasis is disrupted, a shift towards a dysbiotic microbiota, characterized by an increase in anaerobic Gram-negative organisms, initiates an inflammatory cascade in the peri-implant mucosa [Herrera D et al., 2023].

The persistent presence of pathogenic biofilms leads to the development of peri-implant mucositis, a reversible inflammatory lesion confined to the soft tissues, and, if unmanaged, may progress to peri-implantitis, where irreversible bone loss occurs [Heitz-Mayfield LJA et al., 2024]. Studies have shown that even clinically healthy peri-implant sulci can harbor periodontopathogens without signs of inflammation, indicating that the host immune response and the ecological balance of the biofilm are key factors in disease onset [Wada M et al., 2021].

Recent investigations have highlighted that the peri-implant biofilm exhibits distinct microbiological features compared to periodontal biofilm, forming a unique ecological niche characterized by lower microbial diversity and specific species adaptation to the implant environment [Daubert DM et al., 2019]. While early colonization processes appear similar between teeth and implants, mature peri-implant biofilms demonstrate unique bacterial profiles influenced by implant surface properties, abutment connections, and host immune responses. The peri-implant sulcus has been described as a distinct microenvironment where the presence of titanium particles, surface modifications, and the lack of periodontal ligament influence microbial adhesion and biofilm development [Daubert DM et al., 2019]. Moreover, advanced molecular sequencing techniques have revealed that peri-implant sites with disease show a polymicrobial infection dominated not only by classical periodontal pathogens, such as *Porphyromonas gingivalis* and *Tannerella forsythia*, but also by opportunistic organisms like *Staphylococcus aureus* and *Peptostreptococcus ssp*.

The persistence of pathogenic biofilms at implant sites is therefore a critical risk factor throughout all phases of implant therapy — from surgical placement to long-term maintenance. Effective strategies targeting biofilm reduction must account for the unique microbiological and material-related aspects of the peri-implant ecosystem to preserve tissue health and prevent disease progression [Daubert DM et al., 2019].

Effective biofilm control is essential for the long-term maintenance of peri-implant tissue health. Strategies aimed at disrupting biofilm formation and maturation are fundamental to prevent inflammatory changes and to preserve the stability of the supporting bone structures around implants. Current preventive approaches encompass both daily domiciliary oral hygiene measures performed by the patient and periodic professional interventions aimed at the mechanical and chemical disruption of the biofilm [Figuero E et al., 2014; Perussolo J et al., 2024].

In the following sections, the principles and practices of biofilm control will be analyzed, differentiating between domiciliary methods and professional strategies, to provide a comprehensive understanding of their roles in peri-implant disease prevention.

Emerging preventive strategies, such as the use of probiotics to modulate the oral microbiota, targeted local antimicrobial therapies, and adjunctive laser treatments to reduce bacterial load, offer promising perspectives for enhancing peri-implant health. However, their efficacy requires further validation through long-term studies [Dumitriu AS et al. 2023; Ting M et al., 2022; López-Valverde N et al., 2024]. Additional innovative strategies, such as the use of topical antimicrobials (e.g., chlorhexidine gels, minocycline microspheres) have been proposed to enhance biofilm control around implants, particularly in high-risk patients [Boccia G et al., 2023; Elnagdy S et al., 2021].

1.3.1. The role of professional oral hygiene in biofilm management

Daily oral hygiene represents the first and most crucial defense line against plaque accumulation and the development of peri-implant inflammation. The use of manual or electric toothbrushes, interdental brushes, and antimicrobial mouthwashes containing chlorhexidine has proven effective in controlling biofilm formation around implants, especially in patients with reduced manual dexterity or elevated risk profiles [Dreyer H et al., 2018; Derks J et al., 2022].

Professional biofilm management is thus recognized as a cornerstone for the prevention of peri-implant diseases. Current evidence emphasizes that early and consistent disruption of biofilm not only prevents the onset of peri-implant mucositis but also significantly reduces the risk of progression to peri-implantitis [Jepsen S et al., 2015]. Preventive measures should include systematic removal of microbial deposits, monitoring of peri-implant tissue health, and reinforcement of patient-specific oral hygiene protocols. Such strategies are critical to maintaining long-term peri-implant stability, particularly in patients presenting with risk factors such as a history of periodontitis, smoking, or systemic conditions like diabetes [Jepsen S et al., 2015].

A variety of professional instruments and techniques have been developed to optimize biofilm removal while minimizing damage to implant surfaces. Among these, air-polishing with low-abrasive powders such as glycine and erythritol has gained widespread acceptance due to its efficacy in disrupting supra- and subgingival biofilms with minimal alteration of the implant surface [Baldi D et al., 2022; Chen A et al., 2023; Gheorghe DN et al., 2023]. Glycine powders, characterized by their small particle size and low abrasiveness, have shown significant effectiveness in maintaining the integrity of implant surfaces, while erythritol powders, even finer, offer additional benefits in terms of subgingival access and reduced inflammatory response [Liu CC et al., 2024].

Ultrasonic instrumentation with non-metallic tips, such as those coated in PEEK (polyether ether ketone), represents another valuable method for peri-implant biofilm removal. Compared to traditional metal tips, PEEK-coated tips offer the advantage of being less aggressive toward the titanium surface, thereby reducing the risk of surface roughening and maintaining the biocompatibility essential for peri-implant tissue health [Baldi D et al., 2022; Chen A et al., 2023].

Manual instruments, particularly titanium or carbon-fiber curettes, remain an option for specific clinical situations requiring targeted debridement. However, several studies have demonstrated that even supposedly safe materials can cause micro-scratches and alterations if applied with excessive force or inappropriate angulation [Louropoulou A et al., 2015].

The preservation of the implant surface during professional debridement procedures is a critical factor in maintaining peri-implant tissue health. As implant surfaces are often micro-roughened to enhance osseointegration, they are particularly susceptible to damage during mechanical biofilm removal. Surface alterations, such as increased roughness, scratches, or contamination, can facilitate bacterial colonization and impair the long-term stability of the peri-implant tissues [Louropoulou A et al., 2015].

Several studies have compared the effects of various debridement instruments on implant surfaces. Traditional metal curettes and metallic ultrasonic tips have been shown to induce significant surface alterations, including scratching and removal of the oxide layer that protects the titanium from corrosion [Louropoulou A et al., 2015; Yen Nee W et al., 2022]. Consequently, their use in peri-implant maintenance is generally discouraged unless specifically indicated and performed with extreme caution.

To minimize the risk of surface damage, non-metallic instruments have been developed, including curettes made of carbon fiber, resin, or titanium-coated materials, as well as ultrasonic tips coated with polyether ether ketone (PEEK) [Yen Nee W et al., 2022]. PEEK-coated ultrasonic tips offer an effective compromise between mechanical debridement efficacy and surface preservation, allowing for the disruption of the biofilm with a lower risk of surface abrasion.

Air-polishing systems utilizing low-abrasive powders, such as glycine or erythritol, have emerged as preferred alternatives for biofilm removal around implants. Compared to mechanical instruments, air-polishing devices produce significantly less surface alteration while effectively removing bacterial deposits from both supra- and subgingival sites [Baldi D et al., 2022; Yen Nee W et al., 2022; Delucchi F et al., 2025]. Glycine powders, with their particle size of approximately 25 μm, and erythritol powders, even finer at about 14 μm, are specifically indicated for implant maintenance due to their gentle action on peri-implant tissues and surfaces [Liu et al., 2024; Delucchi F et al., 2025; Gómez-Rueda AY et al., 2025].

Regular professional check-ups are fundamental in the early detection of inflammatory signs, such as bleeding on probing or an increase in peri-implant probing depth. Timely intervention at these stages can halt the progression from reversible mucositis to irreversible peri-implantitis [Jepsen S et al., 2015; Renvert S et al., 2015]. In clinical practice, the choice of debridement technique must be carefully tailored to the implant surface characteristics, the extent of biofilm accumulation, and the clinical status of the peri-implant tissues. A minimally invasive approach aimed at preserving surface integrity while achieving effective biofilm disruption is fundamental for the long-term success of implant-supported rehabilitations [Herrera D et al., 2023].

Among adjunctive technologies explored to enhance peri-implant biofilm control, laser-assisted therapies — including diode and Er:YAG lasers — have shown promise in peri-implant decontamination by offering significant bactericidal effects; however, their use should be regarded as complementary rather than a replacement for mechanical debridement [Chen A et al., 2023]. Additionally, other innovative strategies, such as the administration of probiotics to modulate the oral microbiota, and the targeted use of antibiotics or topical antimicrobials in predisposed patients, have been investigated for their potential benefits. Nevertheless, the clinical efficacy of these adjunctive therapies requires further validation through long-term studies [Boccia et al., 2023; Kligman et al., 2021; Araújo TG et al., 2024; López-Valverde N et al., 2024; Kochar SP et al., 2022]. Thus, an integrated approach combining effective at-home oral hygiene practices, professional biofilm disruption, and personalized preventive measures remains fundamental for preserving peri-implant tissue health and ensuring the long-term success of implant therapy.

In addition to mechanical strategies, the role of patient education cannot be overstated. Each professional maintenance visit offers an opportunity to reinforce proper oral hygiene practices, motivate the patient, and adapt home care instructions according to clinical findings. A proactive, collaborative approach between the dental professional and the patient is crucial for achieving long-term peri-implant health and the overall success of implant therapy [Kracher CM et al. 2010; Gulati M et al., 2014].

Given the centrality of surface preservation and biofilm disruption, the following sections will explore two of the most evidence-based and widely adopted techniques for peri-implant maintenance: air-polishing with erythritol powders, and ultrasonic instrumentation with PEEK-coated tips.

*1.3.1.1. **Air-polishing with erythritol-based powder***

In the context of non-surgical peri-implant therapy, air-polishing with low-abrasive powders has emerged as a pivotal innovation in professional biofilm management. Among these, erythritol, a sugar alcohol with a particle size of approximately 14 μm, has gained considerable attention for its favorable balance between clinical efficacy and safety on implant surfaces [Liu CC et al., 2024; Delucchi F et al., 2025; Gómez-Rueda AY et al. 2025; Clementini et al., 2023].

The unique physicochemical characteristics of erythritol—namely, its low abrasiveness, high solubility, and hydrophilic nature—render it particularly suitable for both supragingival and subgingival application [Gheorghe DN et al., 2023; Araújo TG et al., 2024]. Unlike more abrasive powders like sodium bicarbonate, erythritol particles are gentle on titanium surfaces, preserving their microtopography while still allowing for efficient mechanical disruption of the biofilm [Baldi et al., 2022; Louropoulou A et al., 2015; Yen Nee W et al., 2022]. This is of critical importance in peri-implant maintenance, where preserving the integrity of the implant surface directly impacts the long-term stability of peri-implant tissues.

From a clinical perspective, erythritol-based air-polishing has shown consistent benefits in reducing key inflammatory parameters such as bleeding on probing (BoP), probing pocket depth (PPD), and mucosal inflammation in patients with peri-implant mucositis [Delucchi F et al., 2025]. A recent randomized controlled trial by Clementini M et al. (2023) compared the adjunctive use of erythritol powder and Er:YAG laser in non-surgical peri-implantitis therapy. Both treatments resulted in improvements in clinical parameters, but erythritol displayed a more favorable safety profile and shorter chair time, which could translate into higher patient compliance and satisfaction [Clementini M et al., 2023].

Microbiologically, erythritol is not merely a mechanical agent. Studies have shown that it can inhibit the growth and metabolic activity of specific periodontopathogens, including *Porphyromonas gingivalis* and *Fusobacterium nucleatum*, while preserving the balance of commensal flora [Kochar SP et al., 2022]. This selective antimicrobial action supports the concept of biofilm modulation rather than broad-spectrum microbial eradication, aligning with modern principles of ecological plaque control.

The safety of repeated use has been affirmed both in vitro and in vivo. Delucchi F et al. (2025) reported no significant alteration in surface roughness or microstructure of titanium implants even after multiple sessions of erythritol air-polishing [Delucchi F et al. 2025]. This finding is corroborated by Jepsen S et al.

(2015), who included erythritol among the recommended instruments for routine supportive implant care within the European Federation of Periodontology (EFP) guidelines [Jepsen S et al., 2015].

Furthermore, erythritol-based protocols have been integrated into structured maintenance programs, particularly for patients with previous history of periodontitis or systemic conditions such as diabetes. Araújo TG et al. (2024) emphasized its role in long-term supportive therapy, highlighting lower recurrence rates of peri-implant mucositis and reduced need for invasive interventions when erythritol is used regularly [Araújo TG et al., 2024].

Herrera et al. (2023), in their S3-level clinical guidelines, have also endorsed erythritol air-polishing as part of the armamentarium for non-surgical peri-implant disease management. The cumulative evidence indicates that erythritol is not only safe but also efficacious in delaying or reversing early signs of inflammation, thus preventing progression to peri-implantitis [Herrera D et al., 2023; Roccuzzo et al., 2021; Clementini M et al., 2023].

In conclusion, air-polishing with erythritol powder represents a minimally invasive, evidence-based, and biologically respectful strategy for the professional management of peri-implant biofilm. Its combination of clinical effectiveness, microbiological modulation, and surface preservation underscores its growing importance in both active therapy and long-term maintenance protocols.

1.3.1.2. ***Ultrasonic instrumentation with PEEK inserts***

In the context of non-surgical peri-implant therapy, ultrasonic instrumentation plays a pivotal role in the mechanical disruption of biofilm deposits around dental implants. Traditional metal ultrasonic tips, however, have long raised concerns due to their potential to damage implant surfaces, alter the protective oxide layer, and generate surface roughness conducive to bacterial recolonization [Louropoulou A et al., 2015; Jepsen S et al., 2015]. As a result, the development of non-metallic alternatives has gained momentum, with polyether ether ketone (PEEK)-coated inserts emerging as one of the most promising innovations in this field.

PEEK is a high-performance thermoplastic polymer characterized by excellent mechanical strength, chemical stability, and biocompatibility, making it particularly suitable for biomedical applications, including implant instrumentation [Ivanovski S et al., 2018]. The unique mechanical properties of PEEK allow it to transmit sufficient ultrasonic energy to dislodge biofilm without inducing surface abrasion or deformation, thereby preserving the microtopography and integrity of the titanium implant surface [Yen Nee W et al., 2022]. This is especially relevant considering that roughened surfaces, while beneficial for osseointegration, are more vulnerable to damage during debridement procedures and more susceptible to bacterial adhesion in case of iatrogenic alteration [Daubert DM et al., 2019].

Recent studies have highlighted the advantages of PEEK-coated ultrasonic tips in reducing soft tissue trauma and minimizing adverse effects on prosthetic materials such as zirconia or resin-based crowns [Araújo TG et al., 2024; Clementini M et al., 2023]. In particular, in vitro analyses have demonstrated that ultrasonic instrumentation with PEEK inserts results in significantly lower roughness alterations compared to traditional stainless steel or titanium tips, while still ensuring effective removal of bacterial biofilm from both supra- and subgingival surfaces [Delucchi F et al., 2025; Kochar SP et al., 2022].

Clinically, the use of PEEK-coated tips has been associated with improved safety profiles during peri-implant maintenance sessions. The preservation of the implant-abutment interface is of paramount importance, as microdamage in this zone may favor microbial penetration and promote chronic inflammation [Jepsen S et al., 2015; Herrera D et al., 2023]. Moreover, patients receiving maintenance care with ultrasonic instruments equipped with polymer-based tips often report greater comfort during instrumentation, potentially enhancing compliance with supportive therapy regimens [Chen A et al., 2023].

Although direct clinical trials comparing the long-term outcomes of PEEK instrumentation with other modalities are still limited, the growing body of laboratory and preclinical evidence supports its adoption as a standard of care in implant maintenance. Additionally, broader literature on plastic or carbon-fiber instruments provides indirect validation of the protective role of non-metallic materials in peri-implant care [Louropoulou A et al., 2015; Yen Nee W et al., 2022]. Some authors have also suggested that polymer-coated ultrasonic instrumentation may be particularly beneficial in high-risk patients—such as those with a history of periodontitis or diabetes—where tissue preservation is especially critical. Given its combination of mechanical efficacy, biocompatibility, and reduced abrasiveness, PEEK-coated ultrasonic instrumentation represents a viable alternative to conventional metallic debridement tools in peri-implant maintenance protocols. Its role as the comparator in the present clinical study reflects current trends in implant hygiene, where innovations aim not only to eliminate biofilm but also to preserve the structural and biological integrity of implant rehabilitations over time.

II – JUSTIFICATION

II - JUSTIFICATION

The increasing diffusion of implant-supported rehabilitations has significantly improved the quality of life for edentulous and partially edentulous patients. However, the long-term success of dental implants relies not only on correct surgical and prosthetic procedures, but also—critically—on the effectiveness of professional maintenance protocols aimed at preventing peri-implant diseases [Herrera D et al., 2023; Jepsen S et al., 2015;]. Among these, peri-implant mucositis and peri-implantitis are pathological conditions predominantly induced by biofilm accumulation, which may compromise implant survival if not properly managed [Berglundh T et al., 2018; Figuero E et al., 2014].

While the etiopathogenesis of peri-implant inflammation is now well-established, the most effective methods for biofilm removal around implants remain the subject of debate, particularly in the context of maintenance therapy [Herrera D et al., 2023; Heitz-Mayfield LJA et al., 2021]. Traditional mechanical debridement using ultrasonic instruments or hand scalers—although widely used—may carry risks of damaging implant surfaces and prosthetic restorations, especially when materials of high esthetic value and lower mechanical resistance are involved [Louropoulou A et al., 2015; Yen Nee W et al., 2022].

In recent years, air polishing with low-abrasive powders such as erythritol has emerged as a promising alternative for peri-implant maintenance. Its advantages include minimal invasiveness, high patient acceptance, and a reduced risk of surface alteration [Baldi D et al., 2022; Liu CC et al., 2024; Delucchi F et al., 2025]. Nevertheless, evidence from randomized clinical trials directly comparing air polishing with modern ultrasonic instrumentation—especially those using biocompatible tips like PEEK—is still limited, and rarely stratified by prosthetic material, which may influence clinical outcomes [Baldi D et al., 2022; Araújo TG et al., 2024].

Given this context, the present thesis addresses a current and relevant clinical question: Which professional protocol ensures the best peri-implant tissue response during long-term maintenance, and does the type of prosthetic material play a role in treatment efficacy? To answer this, a randomized controlled trial was designed to compare erythritol-based air polishing and ultrasonic debridement with PEEK tips over a 24-month follow-up, assessing their impact on key clinical parameters such as probing pocket depth, bleeding on probing, and plaque index.

This study aims not only to generate high-level scientific evidence on the comparative efficacy of two widely used maintenance protocols, but also to offer practical indications to clinicians regarding material-sensitive approaches in implant maintenance. In doing so, it contributes to a better understanding of personalized prevention strategies in implantology—an increasingly central theme in contemporary dental practice.

Based on the current knowledge gap, the null hypothesis formulated for this study posits that there would be no statistically significant difference in peri-implant clinical outcomes—namely probing pocket depth, bleeding on probing, and plaque index—between patients treated with erythritol-based air polishing and those undergoing ultrasonic debridement with PEEK-coated tips over the 24-month follow-up period.

III – OBJECTIVES

III - OBJECTIVES

The aim of this doctoral research is to investigate and compare the effectiveness of two different professional decontamination protocols—erythritol-based air polishing and ultrasonic instrumentation with PEEK-coated tips—in the context of peri-implant maintenance over a 24-month period.

3.1. MAIN OBJECTIVES

The central objective is to determine which of these two approaches ensures better control of the clinical parameters typically associated with peri-implant health, namely probing pocket depth (PPD), bleeding on probing (BoP), and plaque index (PI). These parameters were selected as they are widely recognized as reliable indicators of peri-implant tissue condition and patient compliance with oral hygiene protocols.

3.2. SPECIFIC OBJECTIVES

- To assess the reduction in probing pocket depth (PPD) in both treatment groups.
- To evaluate changes in bleeding on probing (BoP) over time for each protocol.
- To compare plaque index (PI) values as a measure of biofilm control and oral hygiene efficacy.
- To investigate whether the type of prosthetic crown material—feldspathic ceramic, zirconia, or lithium disilicate—influences the clinical outcomes of the two protocols.

IV – MATERIAL AND METHODS

IV -MATERIAL AND METHODS

This single-center randomized clinical trial was conducted in accordance with ethical and regulatory standards. The study protocol was reviewed and approved by the Institutional Review Board of the University of Pavia (approval number: 2023-0201), and the trial was registered on ClinicalTrials.gov (identifier: NCT06288919) to ensure transparency and accessibility.

4.1. STUDY SETTING AND PARTICIPANTS

The study was conducted at the Unit of Dental Hygiene, Section of Dentistry, Department of Clinical, Surgical, Diagnostic, and Pediatric Sciences, University of Pavia (Italy). Participants were adults aged between 18 and 70 years, each with at least one functional dental implant restored with a crown made of feldspathic ceramic, zirconia, or lithium disilicate. All patients had to demonstrate adequate oral hygiene and willingness to comply with scheduled follow-up visits.

Before inclusion, patients received detailed information on study objectives, procedures, risks, and benefits. Written informed consent was obtained from all participants. To ensure participant safety and preserve the methodological integrity of the study, specific exclusion criteria were established. Individuals with cardiac pacemakers were not eligible for inclusion due to the potential risk of interference with electronic devices used during clinical procedures. Similarly, patients with neurological or psychological disorders—such as epilepsy—were excluded, as these conditions could affect treatment responsiveness or pose procedural risks. Pregnant women were also excluded, given that hormonal fluctuations and physiological changes associated with pregnancy might influence the clinical indices under evaluation. These criteria were carefully selected to minimize potential confounding factors and to maintain standardized and safe treatment conditions throughout the duration of the study.

4.2. INTERVENTIONS AND CLINICAL PROTOCOL

After baseline eligibility screening and informed consent, all participants were randomly assigned to one of two treatment groups:

- Group 1 (EAP – Erythritol-based Air-Polishing): Professional supragingival and subgingival decontamination was performed using low-abrasive erythritol powder (AIRFLOW® PLUS, Electro Medical Systems, Nyon, Switzerland), with a standardized exposure of 5 seconds per site, totaling 30 seconds per implant [Hentenaar DFM et al., 2021; Corbella S et al., 2024].
- Group 2 (UPI – Ultrasonic Instrumentation with PEEK Tip): Professional debridement was performed using a piezoelectric handpiece (Mini Piezon, EMS) equipped with a PEEK-coated plastic tip (PI instrument, EMS). The tip was used at low to moderate power settings with continuous water irrigation, targeting each site for 5 seconds, with a total time of 30 seconds per implant [Hentenaar DFM et al., 2021].

Both treatment protocols were performed by the same trained clinician under standardized conditions. No adjunctive antimicrobial agents (e.g., chlorhexidine) or systemic antibiotics were administered at any time during the study to avoid bias in outcome interpretation.

To investigate the potential effect of prosthetic crown materials on treatment efficacy, participants were further stratified into the following subgroups based on the type of crown covering the implant:

- A: feldspathic ceramic (CER)
- B: zirconia (ZIR)
- C: lithium disilicate (DISIL)

This resulted in six study subgroups: Group 1A: EAP-CER; Group 1B: EAP-ZIR; Group 1C: EAP-DISIL; Group 2A: UPI-CER; Group 2B: UPI-ZIR; Group 2C: UPI-DISIL.

The clinical indices used in this study were defined as follows:

- Probing Pocket Depth (PPD): the distance in millimeters from the gingival margin to the bottom of the peri-implant sulcus or pocket, measured at four sites around each implant. It reflects the severity of soft tissue inflammation and the depth of the peri-implant crevice; [Stiller M et al., 2015]. Periodontal probing was conducted at four sites per implant (mesial, distal, buccal, and lingual), in accordance with previously validated protocols [Stiller M et al., 2015; Hentenaar DFM et al., 2021; Corbella S et al., 2024].
- Bleeding on Probing (BoP): the percentage of sites that exhibited bleeding within 30 seconds after gentle probing, used as an indicator of soft tissue inflammation and vascular response [Farina R et al. 2018].
- Plaque Index (PI): the percentage of implant surfaces with visible plaque accumulation, serving as a measure of patient compliance with oral hygiene and overall plaque control [O' Leary TJ et al., 1972].

4.2.1. Clinical workflow at each timepoint

Each participant underwent five study visits over a 24-month period:

- T0 (baseline)
- T1 (6 months)
- T2 (12 months)
- T3 (18 months)
- T4 (24 months)

T0 – Baseline Visit

- Collection of general and dental medical history
- Signing of the informed consent form
- Full-mouth clinical examination (PPD, BoP, PI)

- Dental charting and classification of prosthetic crown material
- Random allocation to treatment group and subgroup
- Professional supragingival and subgingival cleaning:
  - Group 1- EAP: erythritol air-polishing (AIRFLOW® PLUS)
  - Group 2- UPI: ultrasonic debridement with PEEK tip
- Tailored oral hygiene instructions based on individual prosthetic design and risk profile

T1–T4 (6, 12, 18, 24 months)

- Re-evaluation of clinical parameters (PPD, BoP, PI)
- Professional decontamination session as per assigned group
- Reinforcement of oral hygiene instructions
- Documentation of adverse events or prosthetic complications

Clinical parameters were recorded by a blinded and calibrated examiner using a UNC 12 plastic periodontal probe (Hu-Friedy, Chicago, IL, USA), at four sites per implant (mesial, distal, buccal, and lingual).

4.3. RANDOMIZATION AND BLINDING

Participants were randomized into the two treatment groups using a simple 1:1 allocation method, generated by a computer-based randomization sequence. Allocation was concealed using sequentially numbered, opaque, sealed envelopes, managed by an independent researcher not involved in clinical procedures or outcome assessments. This ensured blinding of allocation and reduced potential selection bias.

Although clinicians were necessarily aware of the intervention due to the nature of the devices, outcome assessments were performed by a blinded examiner.

4.4. SAMPLE SIZE CALCULATION

The sample size calculation was based on detecting a significant difference in the Plaque Index, considered the primary outcome. Drawing on previous studies [Stiller M et al., 2015], with an alpha of 0.05, power of 85%, expected mean of 0.41, mean difference of 0.30, and standard deviation of 0.55, the required sample size was estimated at 60 patients per group.

4.5. STATISTICAL ANALYSIS

All statistical analyses were performed using R software (version 3.1.3, R Foundation for Statistical Computing, Vienna, Austria). Descriptive statistics (mean, standard deviation, median, range) were calculated for all variables.

Normality of data distribution was assessed using the Shapiro–Wilk test. Given the non-normal distribution of most variables, non-parametric tests were used. In particular, the Friedman test was applied for repeated measures, followed by Dunn's multiple comparison post hoc test. A p-value of <0.05 was considered statistically significant.

Separate analyses were performed:

- Cumulatively, for a global comparison between EAP and UPI
- By subgroups, for material-specific comparisons (e.g., EAP-ZIR vs. UPI-ZIR)

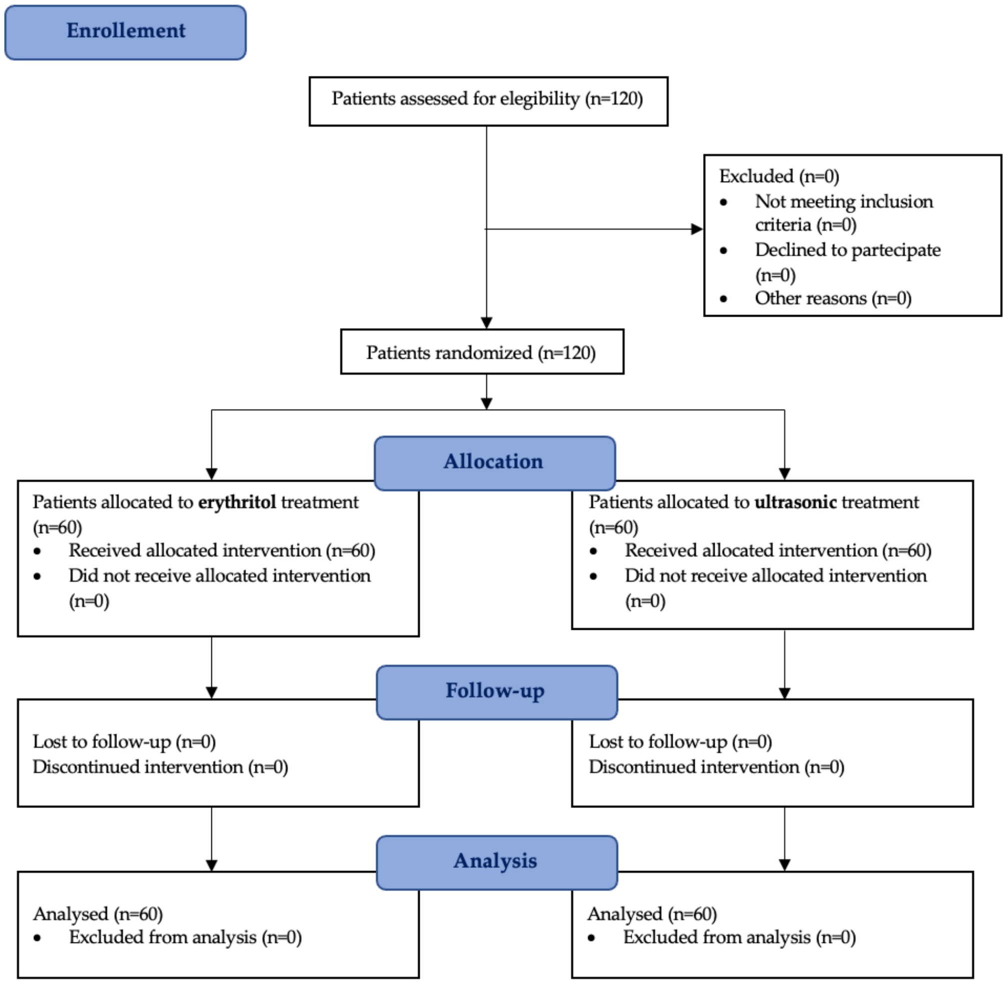

Figure 1. Flow diagram illustrating patient selection, randomization, and follow-up

A total of 120 patients were assessed for eligibility and randomized equally into two groups: erythritol air-polishing and ultrasonic treatment. No patients were excluded, lost to follow-up, or discontinued, and all were included in the final analysis.

V – RESULTS

V - RESULTS

This section presents the outcomes of the study, structured into two main parts. The first part provides a demographic analysis of the participants, reported both cumulatively and by subgroups, based on treatment modality and prosthetic material. The second part describes the clinical results for each of the evaluated parameters—Probing Pocket Depth (PPD), Bleeding on Probing (BoP), and Plaque Index (PI)—with a distinction between cumulative data and subgroup-specific analyses.

5.1. DEMOGRAPHIC CHARACTERISTICS

A total of 120 patients were enrolled and completed the study protocol, with no dropouts or loss to follow-up during the 24-month period. The overall population included 62 males (51.7%) and 58 females (48.3%), with a balanced gender distribution across the two treatment arms. The mean age of all participants was 49.94 ± 10.63 years, ranging from 27 to 69 years.

5.1.1. Cumulative population analysis

Following random allocation, 60 patients were assigned to the erythritol air-polishing group (Group 1-EAP) and 60 to the ultrasonic debridement group with PEEK tips (Group 2-UPI). The age and gender profiles were comparable between the two groups (Table 1). Specifically, the erythritol group included 29 males (mean age 49.24 ± 10.38 years) and 31 females (mean age 48.52 ± 11.98 years). In the ultrasonic group, 33 males (mean age 51.21 ± 11.15 years) and 27 females (mean age 50.81 ± 8.66 years) were included. Statistical analysis confirmed the absence of significant differences between the groups in terms of age or gender ($p > 0.05$), validating the homogeneity of the baseline population (Table 1).

Table 1. Cumulative demographic characteristics of patients in Group 1-EAP (erythritol-based air-polishing) and Group 2-UPI (ultrasonic instrumentation with PEEK inserts).

Patients	Sex	n (%)	Mean age (SD)
Total	Males	62 (51.67%)	50.29 (10.76)
	Females	58 (48.33%)	49.59 (10.54)
Group 1-EAP	Males	29 (24.17%)	49.24 (10.38)
	Females	31 (25.83%)	48.52 (11.98)
Group 2-UPI	Males	33 (27.50%)	51.21 (11.15)
	Females	27 (22.50%)	50.81 (8.66)

Abbreviations: EAP = erythritol-based air polishing; UPI = ultrasonic instrumentation with PEEK inserts; SD = standard deviation.

5.1.2. Subgroup distribution by prosthetic material

To assess the potential influence of the prosthetic crown material on treatment response, the population was stratified into six subgroups based on the material used for the restoration: feldspathic ceramic, zirconia, or lithium disilicate. Each restorative category included 40 patients, evenly divided between the two treatment protocols, ensuring comparability across the study arms (Table 2).

In the feldspathic ceramic subgroup, the erythritol-treated group (EAP) consisted of 9 males with a mean age of 48.00 ± 9.99 years and 11 females with a mean age of 45.45 ± 12.23 years (Table 2). In the corresponding ultrasonic group (UPI), there were 12 males and 8 females, whose mean ages were 51.33 ± 12.11 and 51.63 ± 9.81 years, respectively (Table 2). Within the zirconia subgroup, the EAP group included 11 males (mean age 52.82 ± 8.96 years) and 9 females (mean age 52.56 ± 10.48 years). The UPI group in this category also comprised 11 males and 9 females, with mean ages of 50.64 ± 12.65 and 51.89 ± 5.78 years, respectively. For the lithium disilicate subgroup, the EAP group consisted of 9 males and 11 females, with mean ages of 46.11 ± 10.49 and 48.27 ± 11.38 years, respectively (Table 2). The UPI group included 9 males (mean age 52.00 ± 7.06 years) and 11 females (mean age 49.18 ± 8.73 years) (Table 2).

Across all restorative categories, the demographic variables remained evenly distributed, with no notable discrepancies in age or sex. This confirms that any subsequent differences observed in clinical performance are unlikely to be confounded by demographic imbalance and can be attributed to the treatment protocols or prosthetic materials under investigation (Table 2).

Table 2. Demographic distribution of participants based on the prosthetic crown material used (feldspathic ceramic, zirconia, lithium disilicate) in both treatment groups.

Patients	Sex	n (%)	Mean age (SD)
Total	Males	62 (51.67%)	50.29 (10.76)
	Females	58 (48.33%)	49.59 (10.54)
Group 1A EAP-CER	Males	9 (7.50%)	48.00 (9.99)
	Females	11 (9.17%)	45.45 (12.23)
Group 1B EAP-ZIR	Males	11 (9.17%)	52.82 (8.96)
	Females	9 (7.50%)	52.56 (10.48)
Group 1C EAP-DISIL	Males	9 (7.50%)	46.11 (10.49)
	Females	11 (9.17%)	48.27 (11.38)
Group 2A UPI-CER	Males	12 (10.00%)	51.33 (12.11)
	Females	8 (6.67%)	51.63 (9.81)
Group 2B UPI-ZIR	Males	11 (9.17%)	50.64 (12.65)
	Females	9 (7.50%)	51.89 (5.78)
Group 2C UPI-DISIL	Males	9 (7.50%)	52.00 (7.06)
	Females	11 (9.17%)	49.18 (8.73)

Abbreviations: EAP = erythritol-based air polishing; UPI = ultrasonic instrumentation with PEEK inserts; CER = feldspathic ceramic; ZIR = zirconia; DISIL = lithium disilicate; SD = standard deviation.

5.2. PROBING POCKET DEPTH (PPD)

Probing Pocket Depth (PPD) is one of the most widely used clinical parameters in the assessment of peri-implant tissue health. It provides valuable information on the extent of inflammation and soft tissue detachment around the implant. In this study, changes in PPD were monitored over time to evaluate the impact of the two decontamination protocols on the reduction of peri-implant pocket depth. The results are reported both cumulatively—comparing the overall effectiveness of erythritol-based air polishing and ultrasonic instrumentation with

PEEK tips—and within subgroups, in order to assess whether the type of prosthetic material influenced clinical performance.

5.2.1. Cumulative population analysis

5.2.1.1. *Descriptive analysis*

The descriptive analysis of cumulative data regarding probing pocket depth (PPD) revealed a progressive reduction in mean values over time in both treatment groups (Table 3). Specifically, in the group treated with erythritol-based air polishing, the mean PPD decreased from 3.70 ± 0.55 mm at baseline (T0) to 2.62 ± 0.45 mm at the final follow-up (T4), corresponding to an overall mean reduction of 1.08 mm (Table 3). Similarly, the group treated with ultrasonic instrumentation equipped with PEEK inserts showed a decrease in mean PPD values from 3.50 ± 0.54 mm to 2.78 ± 0.37 mm, resulting in a total reduction of 0.72 mm (Table 3).

These descriptive results suggest that both protocols were associated with a reduction in peri-implant pocket depth over the 24-month follow-up (Table 3).

Table 3. Descriptive analysis of Probing Pocket Depth (PPD) in Group 1-EAP (erythritol-based air-polishing) and Group 2-UPI (ultrasonic instrumentation with PEEK inserts).

Group	Time	Mean	St Dev	Min	Median	Max
Group 1 EAP	T0	3.70	0.55	3.00	4.00	5.00
	T1	3.23	0.51	2.00	3.00	4.50
	T2	2.90	0.43	2.00	3.00	4.00
	T3	2.85	0.35	2.00	3.00	3.00
	T4	2.62	0.45	2.00	3.00	3.00
Group 2 UPI	T0	3.50	0.54	3.00	3.25	4.50
	T1	3.24	0.44	2.50	3.00	4.50
	T2	2.98	0.33	2.00	3.00	4.00
	T3	2.91	0.28	2.00	3.00	3.00
	T4	2.78	0.37	2.00	3.00	3.00

Abbreviations: PPD = Probing Pocket Depth; EAP = erythritol-based air polishing; UPI = ultrasonic instrumentation with PEEK inserts; SD = standard deviation; T0–T4 = timepoints from baseline to 24 months.

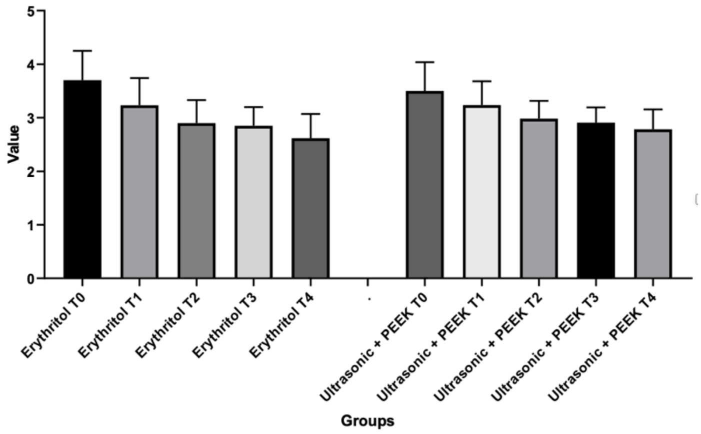

Figure 2. Temporal changes in Probing Pocket Depth (PPD) in the two treatment groups (erythritol and ultrasonic + PEEK)

This figure graphically illustrates the trend in Probing Pocket Depth (PPD) over time in the two treatment groups (EAP and UPI) from baseline (T0) to 24 months (T4). The visual representation highlights the overall reduction observed in both groups and enables a direct comparison of their temporal trajectories. In both groups, a progressive decrease in mean PPD values is evident throughout the follow-up period. In the EAP group, the reduction appears more pronounced in the initial phases (T0–T2), with a tendency toward stabilization thereafter. The UPI group shows a similar decreasing trend, albeit more gradual and consistent over time. The error bars, representing standard deviation, indicate a reduction in inter-subject variability as follow-up progresses, especially in the EAP group. However, despite these visual differences, no statistically significant differences were detected between the two treatment protocols, confirming that both approaches were comparably effective in reducing peri-implant probing depths over the 24-month period (Figure 2).

5.2.1.2. *Inferential analysis*

The inferential statistical analysis confirmed the significance of the temporal changes observed in both treatment groups (Table 4). The Friedman test, applied to evaluate intra-group differences over time, yielded statistically significant results ($p < 0.0001$) for both the erythritol group and the ultrasonic + PEEK group, indicating a consistent reduction in PPD values throughout the follow-up period (Table 4).

Post-hoc comparisons using Dunn's multiple comparison test further supported these findings. In the erythritol group, statistically significant reductions in PPD were observed between T0 and each of the subsequent time points (T2, T3, and T4), with the most substantial difference occurring between T0 and T4 ($p < 0.0001$) (Table 4). The ultrasonic + PEEK group also demonstrated a significant reduction in PPD values over time, although the magnitude of change was consistently smaller and the pattern of improvement less homogeneous across the different time points (Table 4).

The intergroup comparisons at each timepoint, including T4, did not reveal statistically significant differences between the two treatment groups (Table 4). Although the erythritol group showed a trend toward greater PPD reduction, the differences were not statistically significant ($p > 0.05$), indicating comparable clinical efficacy over the 24-month period (Table 4).

Table 4. Dunn's multiple comparisons test of Probing Pocket Depth (PPD) in Group 1-EAP (erythritol-based air-polishing) and Group 2-UPI (ultrasonic instrumentation with PEEK inserts).

Intra-group comparisons (Group 1-EAP)		
Comparison	**Adjusted p-value**	**Significance**
T0 vs T2	<0.0001	****
T0 vs T3	<0.0001	****
T0 vs T4	<0.0001	****
T1 vs T3	0.05	*
T1 vs T4	<0.0001	****
Intra-group comparisons (Group 2-UPI)		
Comparison	**Adjusted p-value**	**Significance**
T0 vs T2	0	***
T0 vs T3	<0.0001	****

T0 vs T4	<0.0001	****
T1 vs T4	0	***
Inter-group comparisons (Group 1-EAP vs Group 2-UPI)		
Comparison	**Adjusted p-value**	**Significance**
T0	>0.9999	Ns
T1	>0.9999	Ns
T2	>0.9999	Ns
T3	>0.9999	Ns
T4	>0.9999	Ns

*Abbreviations: PPD = Probing Pocket Depth; EAP = erythritol-based air polishing; UPI = ultrasonic instrumentation with PEEK inserts; Significance levels: ns = not significant (p > 0.05); * p < 0.05; ** p < 0.01; *** p < 0.001; **** p < 0.0001.*

5.2.2. Subgroup distribution by prosthetic material

5.2.2.1. *Descriptive analysis*

When analyzing the data by subgroup according to prosthetic material, all six subgroups demonstrated a progressive reduction in probing pocket depth (PPD) over time (Table 5). In the erythritol-treated groups, mean PPD values decreased from 3.85 mm to 2.68 mm in subgroup EAP-CER, from 3.70 mm to 2.58 mm in EAP-ZIR, and from 3.58 mm to 2.60 mm in EAP-DISIL (Table 5). Similarly, the ultrasonic + PEEK groups showed reductions from 3.58 mm to 2.60 mm across all materials (Table 5). The magnitude of reduction was consistently greater in the EAP subgroups, with mean decreases ranging from 0.98 to 1.17 mm, compared to a mean reduction of 0.98 mm in all UPI subgroups (Table 5). Final PPD values at T4 were generally lower in the erythritol groups, suggesting a trend toward better outcomes, although the differences were not substantial (Table 5). These findings indicate that the effectiveness of both protocols is not significantly influenced by the type of restorative material.

Table 5. Descriptive analysis of Probing Pocket Depth (PPD) in all subgroups.

Group	T0 Mean ± SD	T4 Mean ± SD	Δ
Group 1A	3.85 ± 0.50	2.68 ± 0.47	-1.17

EAP-CER			
Group 1B **EAP-ZIR**	3.70 ± 0.64	2.58 ± 0.47	-1.12
Group 1C **EAP-DISIL**	3.58 ± 0.52	2.60 ± 0.45	- 0.98
Group 2A **UPI-CER**	3.58 ± 0.52	2.60 ± 0.45	- 0.98
Group 2B **UPI-ZIR**	3.58 ± 0.52	2.60 ± 0.45	- 0.98
Group 2C **UPI-DISIL**	3.58 ± 0.52	2.60 ± 0.45	- 0.98

Abbreviations: PPD = Probing Pocket Depth; SD = standard deviation; Δ = absolute mean difference between T0 and T4; EAP = erythritol-based air polishing; UPI = ultrasonic instrumentation with PEEK inserts; CER = feldspathic ceramic; ZIR = zirconia; DISIL = lithium disilicate.

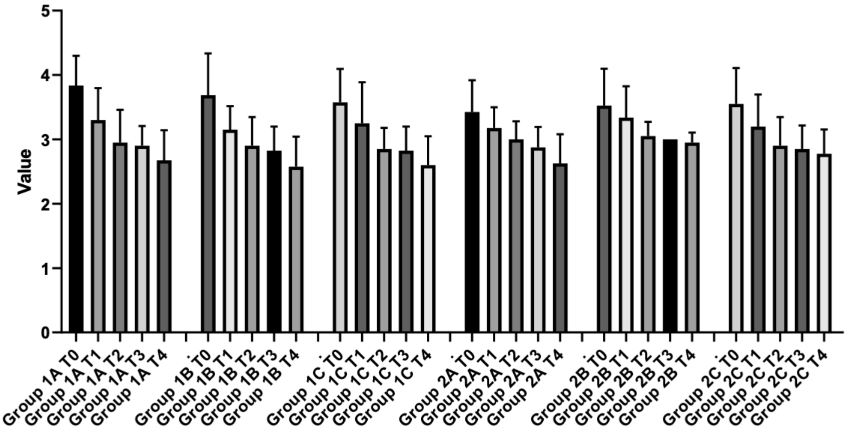

Figure 3. Temporal changes in Probing Pocket Depth (PPD) in all subgroups

This graphical representation illustrates the general downward trend in PPD values across all subgroups over the study period. The subgroups treated with erythritol-based air polishing (1A–1C) exhibit a more pronounced and consistent early decrease in PPD, particularly within the first 12 months, with values tending to stabilize by T3. Conversely, the subgroups treated with ultrasonic instrumentation and PEEK inserts (2A–2C) show a more gradual and slightly variable reduction, with final values at T4 comparable to those observed in the EAP subgroups. Although visual differences in the magnitude and timing of improvement can be noted—favoring the erythritol-treated groups—no statistically significant differences were detected between corresponding subgroups at any timepoint (adjusted p > 0.9999). These results reinforce the conclusion that both decontamination protocols led to clinically relevant improvements, and that the type of restorative material did not significantly influence the outcome (Figure 3).

5.2.2.2. *Inferential analysis*

The inferential analysis performed within each subgroup confirmed the statistical significance of the observed reductions in probing pocket depth (PPD) over time (Table 6). The Friedman test revealed highly significant differences across time points in all six subgroups (p < 0.0001), indicating that both treatment protocols were effective in reducing PPD regardless of the prosthetic material (Table 6). Post-hoc analysis with Dunn's test highlighted a more consistent and earlier onset of statistically significant reductions in the erythritol-treated subgroups (Table 6). Specifically, in subgroup EAP-CER, significant differences were already evident between T0 and T2 (p = 0.006), and further consolidated at T3 (p = 0.003) and T4 (p < 0.0001) (Table 6). A similar pattern was observed in EAP-ZIR, where significant reductions occurred from T0 to T3 (p = 0.020) and T4 (p < 0.0001) (Table 6). In EAP-DISIL, significant changes were observed at T3 (p = 0.047) and T4 (p < 0.0001) (Table 6). In contrast, while the ultrasonic + PEEK subgroups also showed statistically significant reductions in PPD, these were generally detected later and were less consistent across the intermediate time points (Table 6). For example, subgroup UPI-CER displayed significant differences only between T0 and T4 (p = 0.009), with no statistically significant changes observed at earlier follow-up visits (Table 6). Subgroup UPI-DISIL showed a similar pattern, with significance reached only between T0 and T4 (p = 0.013) (Table 6). Notably, no significant intra-group differences were observed in UPI-ZIR.

These findings confirm the intra-group effectiveness of both decontamination methods but also suggest that air-polishing with erythritol allows for a faster and more uniform reduction in PPD, independent of the prosthetic material used.

Furthermore, inter-group comparisons between EAP and UPI subgroups did not reveal statistically significant differences in PPD reduction for any prosthetic material at any time point (Table 6). All adjusted p-values were greater than 0.9999 across comparisons from T0 to T4, indicating the absence of significant differences between the two treatment protocols (Table 6). Although no statistical differences were found between groups, the earlier and more consistent reductions observed in the EAP subgroups may suggest a potential clinical advantage, which was not statistically confirmed.

Table 6. Dunn's multiple comparisons test of Probing Pocket Depth (PPD) in all subgroups.

Intra-group comparisons (EAP subgroups)			
Subgroup	**Comparison**	**Adjusted p-value**	**Significance**
EAP-CER	**T0 vs T2**	0.006	**
	T0 vs T3	0.003	**
	T0 vs T4	<0.0001	****
EAP-ZIR	**T0 vs T3**	0.02	*
	T0 vs T4	<0.0001	****
EAP-DISIL	**T0 vs T3**	0.047	*
	T0 vs T4	<0.0001	****
Intra-group comparisons (UPI subgroups)			
Subgroup	**Comparison**	**Adjusted p-value**	**Significance**
UPI-CER	**T0 vs T4**	0.009	**
UPI-DISIL	**T0 vs T4**	0.013	*
Inter-group comparisons (EAP subgroups vs UPI subgroups)			
	Comparison	**Adjusted p-value**	**Significance**
EAP-CER vs UPI-CER	**T0**	>0.9999	Ns
	T1	>0.9999	Ns
	T2	>0.9999	Ns
	T3	>0.9999	Ns
	T4	>0.9999	Ns
EAP-ZIR vs UPI-ZIR	**T0**	>0.9999	Ns
	T1	>0.9999	Ns
	T2	>0.9999	Ns
	T3	>0.9999	Ns
	T4	>0.9999	Ns
	T0	>0.9999	Ns

EAP-DISIL vs UPI-DISIL	**T1**	>0.9999	Ns
	T2	>0.9999	Ns
	T3	>0.9999	Ns
	T4	>0.9999	Ns

Abbreviations: PPD = Probing Pocket Depth; EAP = erythritol-based air polishing; UPI = ultrasonic instrumentation with PEEK inserts; CER = feldspathic ceramic; ZIR = zirconia; DISIL = lithium disilicate.

5.3. BLEEDING ON PROBING

Bleeding on Probing (BoP) is a critical early indicator of mucosal inflammation and is highly predictive of peri-implant disease progression. Monitoring BoP over time allows for a dynamic evaluation of the inflammatory response to treatment. In this study, BoP was recorded at each timepoint to assess the anti-inflammatory efficacy of the two decontamination approaches. The analysis includes cumulative comparisons between the treatment groups and a detailed breakdown by prosthetic material subgroup, to determine whether certain restorative surfaces were associated with a higher or lower inflammatory profile.

5.3.1. Cumulative population analysis

5.3.1.1. Descriptive analysis

At baseline (T0), both treatment groups exhibited elevated mean BOP values: 65.42 ± 26.08 for the erythritol group and 50.83 ± 30.52 for the ultrasonic + PEEK group (Table 7). From T1 onward, a progressive and consistent reduction was observed in both groups, reaching 0.42 ± 3.23 and 2.50 ± 7.56 at T4, respectively (Table 7). The most substantial decrease occurred during the first two time points (T0 to T2), with the erythritol group showing a steeper reduction curve compared to ultrasonic instrumentation. Median values progressively dropped to 0.00 in both groups, and the minimum value remained stable at 0.00 from T1, indicating widespread elimination of bleeding sites (Table 7).

Table 7. Descriptive analysis of Bleeding on Probing (BoP) in Group 1-EAP (erythritol-based air-polishing) and Group 2-UPI (ultrasonic instrumentation with PEEK inserts).

Group	Time	Mean	St Dev	Min	Median	Max
Group 1 EAP	T0	65.42	26.08	25.00	50.00	100.00
	T1	28.33	26.63	0.00	25.00	100.00
	T2	8.75	18.31	0.00	0.00	100.00
	T3	1.67	6.29	0,00	0.00	25.00
	T4	0.42	3.23	0.00	0.00	25.00
Group 2 UPI	T0	50.83	30.52	0.00	50.00	100.00
	T1	28.75	26.37	0.00	25.00	100.00
	T2	10.83	18.04	0.00	0.00	50.00
	T3	4.58	11.73	0.00	0.00	50.00
	T4	2.50	7.56	0.00	0.00	25.00

Abbreviations: BoP = Bleeding on Probing; EAP = erythritol-based air polishing; UPI = ultrasonic instrumentation with PEEK inserts; SD = standard deviation; T0–T4 = timepoints from baseline to 24 months.

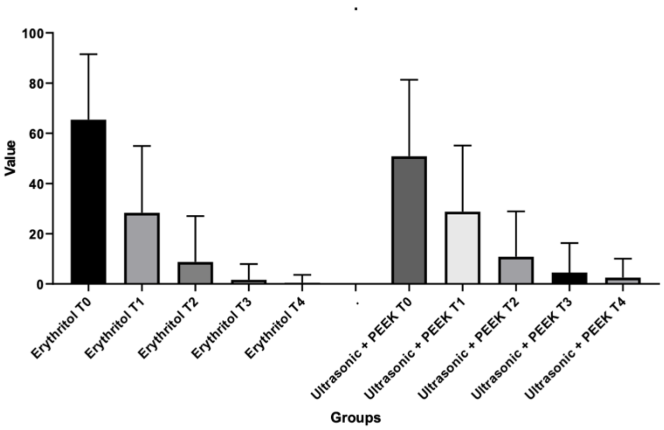

Figure 4. Temporal changes in Bleeding on Probing (BoP) in the two treatment groups (erythritol and ultrasonic + PEEK)

This figure visually depicts the overall reduction in BoP values across both treatment groups over time. A sharp decline is observed in both groups, particularly between T0 and T2, which corresponds to the most intensive phase of improvement. In the erythritol group, the decrease appears more abrupt, with near-complete elimination of bleeding sites already by T3. The ultrasonic group shows a similar pattern, though with a slightly more gradual curve and marginally higher values at each timepoint. Despite the steeper trajectory observed in the EAP group, the two protocols converged toward very low BoP values by T4, and no statistically significant differences were found between them at any timepoint (adjusted p > 0.9999). The error bars suggest higher variability at baseline—particularly in the UPI group—which progressively diminishes as treatment progresses, reflecting a more homogeneous clinical response in both groups over time (Figure 4).

5.3.1.2. *Inferential cumulative analysis*

Friedman's test revealed a highly significant difference among timepoints (p < 0.0001), confirming the effect of time and treatment (Table 8). Dunn’s multiple comparisons test showed significant reductions within the erythritol group from baseline to each subsequent timepoint (T1–T4), with p < 0.0001 in all comparisons. Similarly, the ultrasonic + PEEK group demonstrated significant improvements from T0 to T2 (p < 0.0001) and to T3 (p < 0.0001), with a less marked but still significant reduction up to T4 (p < 0.0001) (Table 8). When comparing the two groups at each timepoint, no significant differences were found (p > 0.9999), although the erythritol group consistently showed numerically lower BOP scores from T1 to T4, suggesting a favorable trend in reducing gingival bleeding over time (Table 8).

Table 8. Dunn’s multiple comparisons test of Probing Pocket Depth (PPD) in Group 1-EAP (erythritol-based air-polishing) and Group 2-UPI (ultrasonic instrumentation with PEEK inserts).

Intra-group comparisons (Group 1-EAP)		
Comparison	**Adjusted p-value**	**Significance**
T0 vs T1	<0.0001	****
T0 vs T2	<0.0001	****
T0 vs T3	<0.0001	****
T0 vs T4	<0.0001	****
T1 vs T3	0	***
T1 vs T4	<0.0001	****
Intra-group comparisons (Group 2-UPI)		
Comparison	**Adjusted p-value**	**Significance**

T0 vs T2	<0.0001	****
T0 vs T3	<0.0001	****
T0 vs T4	<0.0001	****
T1 vs T3	0	***
T1 vs T4	<0.0001	****
Inter-group comparisons (Group 1-EAP vs Group 2-UPI)		
Comparison	**Adjusted p-value**	**Significance**
T0	>0.9999	Ns
T1	>0.9999	Ns
T2	>0.9999	Ns
T3	>0.9999	Ns
T4	>0.9999	Ns

Abbreviations: BoP = Bleeding on Probing; EAP = erythritol-based air polishing; UPI = ultrasonic instrumentation with PEEK inserts; ns = not significant ($p > 0.05$); *Significance levels: *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$; ****$p < 0.0001$.*

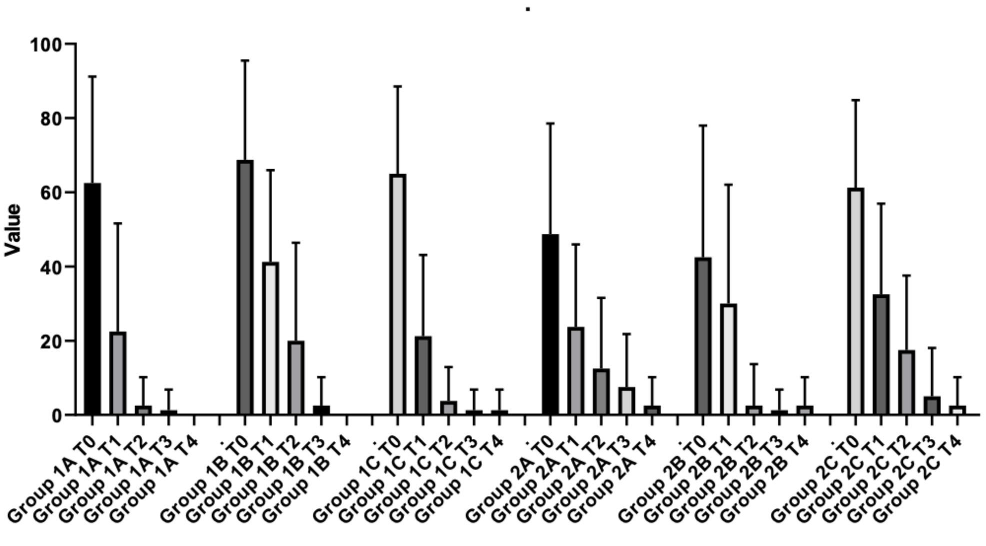

Figure 5. Temporal changes in Bleeding on Probing (BoP) in all subgroups

5.3.2. Subgroup distribution by prosthetic material

5.3.2.1. *Descriptive analysis*

The descriptive analysis of BoP values by prosthetic material subgroup revealed a progressive reduction in mean percentages over time across all six subgroups (Table 9). In the groups treated with erythritol-based air polishing, mean BoP values decreased from 63.8% to 0% in subgroup EAP-CER, from 68.8% to 0% in subgroup EAP-ZIR, and from 66.3% to 1.25% in subgroup EAP-DISIL (Table 9). Similarly, in the groups treated with ultrasonic instrumentation equipped with PEEK inserts, BoP values decreased from 50.0% to 2.5% in subgroup UPI-CER, from 43.8% to 2.5% in subgroup UPI-ZIR, and from 61.3% to 2.5% in subgroup UPI-DISIL (Table 9). The reduction in BoP was more marked and consistent in the erythritol-treated subgroups, with two subgroups (EAP-CER and EAP-ZIR) reaching 0% at T4, and EAP-DISIL showing near-complete resolution (1.25%) (Table 9). In contrast, although BoP also decreased substantially in the ultrasonic + PEEK subgroups, the final values at T4 remained slightly higher (Table 9). These findings suggest a greater effectiveness of the erythritol-based treatment in controlling peri-implant inflammation, regardless of the type of restorative material used.

Table 9. Descriptive analysis of Bleeding on Probing (BoP) in all subgroups.

Group	T0 Mean ± SD	T4 Mean ± SD	Δ
Group 1A EAP-CER	63.8 ± 29.8	0.0 ± 0.0	- 63.8
Group 1B EAP-ZIR	68.8 ± 26.7	0.0 ± 0.0	- 68.8
Group 1C EAP-DISIL	66.3 ± 24.7	1.25 ± 5.59	- 65.1
Group 2A UPI-CER	50.0 ± 31.4	2.5 ± 7.69	- 47.5
Group 2B UPI-ZIR	43.8 ± 37.1	2.5 ± 7.69	- 41.3
Group 2C UPI-DISIL	61.3 ± 23.6	2.5 ± 7.69	- 58.8

Abbreviations: BoP = Bleeding on Probing; SD = standard deviation; Δ = absolute mean difference between T0 and T4; EAP = erythritol-based air polishing; UPI = ultrasonic instrumentation with PEEK inserts; CER = feldspathic ceramic; ZIR = zirconia; DISIL = lithium disilicate.

This figure provides a visual summary of the BoP reduction patterns in all subgroups over time. In the erythritol-based air polishing subgroups (1A–1C), a clear and consistent decline is evident, with BoP values approaching or reaching 0% by T4. These subgroups show minimal variability by the end of follow-up, suggesting a uniform clinical response regardless of prosthetic material.

The ultrasonic + PEEK subgroups (2A–2C) also demonstrate substantial improvement, although final BoP values tend to remain slightly higher. Among these, subgroup 2B (UPI–ZIR) shows greater fluctuation and less consistent reduction, which is reflected in the higher error bars and the lack of statistically significant intra-group change.

Despite the visual trend suggesting a more favorable trajectory in the EAP-treated subgroups, no statistically significant differences were observed between EAP and UPI subgroups at the final timepoint (T4). Overall, the figure supports the conclusion that both protocols effectively reduce BoP over time, with EAP showing a tendency toward more rapid and homogeneous resolution.

5.3.2.2. ***Inferential analysis***

The inferential statistical analysis confirmed the significance of the reductions in BoP across most subgroups (Table 10). The Friedman test showed highly significant differences between time points in five out of six subgroups, indicating a consistent decrease in bleeding scores over the 24-month period; no significant intra-group change was detected in UPI-ZIR, in line with the post-hoc results. Dunn's post-hoc analysis revealed that in the erythritol-treated subgroups (EAP-CER, EAP-ZIR, EAP-DISIL) the reductions were already significant from T2, with all T0 vs T2/T3/T4 comparisons reaching significance ($p < 0.0001$ for EAP-CER and EAP-DISIL; $p = 0.034$ for EAP-ZIR at T0 vs T2) (Table 10). At T4, BoP reached 0% in EAP-CER and EAP-ZIR, while EAP-DISIL showed near-zero values with minimal residual bleeding. In the ultrasonic + PEEK subgroups (UPI-CER, UPI-ZIR, UPI-DISIL), statistically significant reductions were also observed, but their magnitude and timing varied: UPI-CER showed significance at T3 and T4, UPI-DISIL at T3 and T4, whereas UPI-ZIR did not display significant intra-group changes (Table 10). These results reinforce the clinical effectiveness of both decontamination protocols and highlight the earlier and more consistent anti-inflammatory response with erythritol-based air polishing across different prosthetic materials; however, matched inter-group comparisons at T4 within each material were not significant, indicating comparable BoP endpoints at 24 months (Table 10).

Table 10. Dunn's multiple comparisons test of Bleeding on Probing (BoP) in all subgroups.

Intra-group comparisons (EAP subgroups)			
Subgroup	**Comparison**	**Adjusted p-value**	**Significance**
EAP-CER	**T0 vs T2**	<0.0001	****
	T0 vs T3	<0.0001	****
	T0 vs T4	<0.0001	****
EAP-ZIR	**T0 vs T2**	0.034	*
	T0 vs T3	<0.0001	****
	T0 vs T4	<0.0001	****
	T1 vs T3	0.033	*
	T1 vs T4	0.006	**
EAP-DISIL	**T0 vs T2**	<0.0001	****
	T0 vs T3	<0.0001	****
	T0 vs T4	<0.0001	****
Intra-group comparisons (UPI subgroups)			
Subgroup	**Comparison**	**Adjusted p-value**	**Significance**
UPI-CER	**T0 vs T3**	0.046	*
	T0 vs T4	0.002	**
UPI-DISIL	**T0 vs T3**	0.0001	***
	T0 vs T4	<0.0001	****
Inter-group comparisons (EAP subgroups vs UPI subgroups)			
	Comparison	**Adjusted p-value**	**Significance**
EAP-CER vs UPI-CER	**T0**	>0.9999	Ns
	T1	>0.9999	Ns
	T2	>0.9999	Ns

	T3	>0.9999	Ns
	T4	>0.9999	Ns
EAP-ZIR vs UPI-ZIR	**T0**	>0.9999	Ns
	T1	>0.9999	Ns
	T2	>0.9999	Ns
	T3	>0.9999	Ns
	T4	>0.9999	Ns
EAP-DISIL vs UPI-DISIL	**T0**	>0.9999	Ns
	T1	>0.9999	Ns
	T2	>0.9999	Ns
	T3	>0.9999	Ns
	T4	>0.9999	Ns

Abbreviations: *BoP = Bleeding on Probing;* EAP = erythritol-based air polishing; UPI = ultrasonic instrumentation with PEEK inserts; CER = feldspathic ceramic; ZIR = zirconia; DISIL = lithium disilicate; ns = not significant ($p > 0.05$); Significance levels: *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$; ****$p < 0.0001$.

5.4. PLAQUE INDEX (PI)

The Plaque Index (PI) measures the presence of visible biofilm on implant surfaces and reflects the patient's oral hygiene effectiveness as well as the treatment's contribution to plaque control. Given its role in the onset and progression of peri-implant disease, PI is a fundamental clinical index in maintenance protocols. In this trial, PI was assessed over 24 months to determine how effectively each protocol supported plaque reduction. The results are presented cumulatively and by prosthetic material subgroup, enabling a nuanced understanding of how biofilm accumulation varied according to treatment and surface characteristics.

5.4.1. Cumulative population analysis

5.4.1.1. Descriptive analysis

The descriptive statistics revealed a progressive reduction in Plaque Index (PI) values over time in both treatment groups (Table 11). At baseline (T0), the mean PI was slightly higher in the erythritol group (67.50 ± 22.22) compared to the ultrasonic + PEEK group (54.58 ± 27.42) (Table 11). From T1 onwards, both groups showed a marked and continuous decline in plaque accumulation. The erythritol group reached a mean of 0 at T3 and T4, indicating a complete plaque removal in all subjects (Table 11). Similarly, the ultrasonic + PEEK group showed progressive reduction, although with slightly higher residual values at each timepoint, reaching a mean of 2.50 ± 7.56 at T4 (Table 11). These results suggest a consistent efficacy of both protocols in plaque control, with erythritol achieving a faster and more complete reduction within the observation period.

Table 11. Descriptive analysis of Plaque Index (PI) in Group 1-EAP (erythritol-based air-polishing) and Group 2-UPI (ultrasonic instrumentation with PEEK inserts.

Group	Time	Mean	St Dev	Min	Median	Max
Group 1 EAP	T0	67.50	22.22	25.00	50.00	100.00
	T1	22.92	20.73	0.00	25.00	50.00
	T2	6.25	13.52	0.00	0.00	50.00
	T3	0.00	0.00	0.00	0.00	0.00
	T4	0.00	0.00	0.00	0.00	0.00
Group 2 UPI	T0	54.58	27.42	0.00	50.00	100.00
	T1	36.67	26.63	0.00	50.00	100.00
	T2	19.17	23.18	0.00	0.00	75.00
	T3	13.33	20.31	0.00	0.00	75.00
	T4	2.50	7.56	0.00	0.00	25.00

Abbreviations: *PI = Plaque Index; EAP = erythritol-based air polishing; UPI = ultrasonic instrumentation with PEEK inserts; SD = standard deviation; T0–T4 = timepoints from baseline to 24 months.*

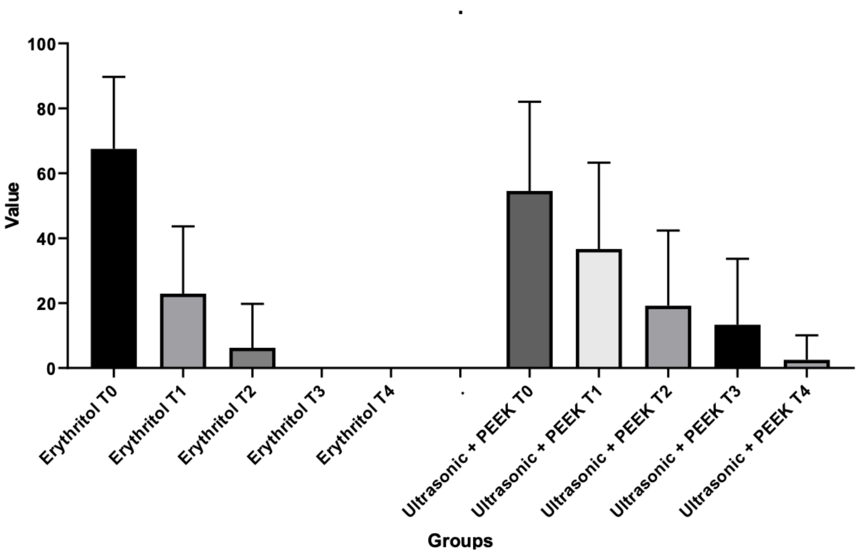

Figure 6. Temporal changes in Plaque Index (PI) in the two treatment groups (erythritol and ultrasonic + PEEK)

The figure highlights a clear downward trend in plaque accumulation across both treatment protocols over the 24-month period. In the EAP group, PI values exhibit a steep decline from T0 to T2, reaching complete resolution by T3, as indicated by the mean value of zero maintained through T4. This suggests a rapid and sustained plaque control effect associated with erythritol-based air polishing. In the UPI group, the reduction in PI is also evident, although more gradual. Residual plaque is still present at each timepoint, with slightly higher variability, particularly during the initial phases of treatment. Despite this, the trend remains consistently favorable throughout the observation period. Overall, both treatments appear effective in reducing plaque levels, with the EAP group achieving faster and more complete results. The visual trajectory supports the descriptive findings, indicating that the choice of decontamination protocol may influence the timing and extent of plaque resolution (Figure 6).

*5.4.1.2. **Inferential analysis***

Statistical analysis using the Friedman test confirmed significant differences over time within both treatment groups ($p < 0.0001$) (Table 12). Dunn's multiple comparison test showed that in the erythritol group (EAP), all timepoints were significantly different from baseline, with highly significant reductions already from T1 (p < 0.0001) and complete absence of plaque from T3. In the ultrasonic + PEEK group (UPI), significant reductions in plaque were observed from T2 onward (p < 0.0001) (Table 12). Inter-group comparisons revealed no statistically significant differences between the EAP and UPI groups at any timepoint, including T4 (adjusted p > 0.9999), confirming comparable performance between the two protocols in terms of plaque reduction over time (Table 12).

Table 12. Dunn's multiple comparisons test of Plaque Index (PI) in Group 1-EAP (erythritol-based air-polishing) and Group 2-UPI (ultrasonic instrumentation with PEEK inserts).

<table>
<tr><th colspan="3">Intra-group comparisons (Group 1-EAP)</th></tr>
<tr><th>Comparison</th><th>Adjusted p-value</th><th>Significance</th></tr>
<tr><td>T0 vs T1</td><td><0.0001</td><td>****</td></tr>
<tr><td>T0 vs T2</td><td><0.0001</td><td>****</td></tr>
<tr><td>T0 vs T3</td><td><0.0001</td><td>****</td></tr>
<tr><td>T0 vs T4</td><td><0.0001</td><td>****</td></tr>
<tr><td>T1 vs T4</td><td>0.04</td><td>*</td></tr>
<tr><td>T1 vs T3</td><td><0.0001</td><td>****</td></tr>
<tr><td>T1 vs T4</td><td><0.0001</td><td>****</td></tr>
<tr><th colspan="3">Intra-group comparisons (Group 2-UPI)</th></tr>
<tr><th>Comparison</th><th>Adjusted p-value</th><th>Significance</th></tr>
<tr><td>T0 vs T2</td><td><0.0001</td><td>****</td></tr>
<tr><td>T0 vs T3</td><td><0.0001</td><td>****</td></tr>
<tr><td>T0 vs T4</td><td><0.0001</td><td>****</td></tr>
<tr><td>T1 vs T3</td><td>0</td><td>***</td></tr>
<tr><td>T1 vs T4</td><td><0.0001</td><td>****</td></tr>
<tr><th colspan="3">Inter-group comparisons (Group 1-EAP vs Group 2-UPI)</th></tr>
<tr><th>Comparison</th><th>Adjusted p-value</th><th>Significance</th></tr>
<tr><td>T0</td><td>>0.9999</td><td>Ns</td></tr>
<tr><td>T1</td><td>>0.9999</td><td>Ns</td></tr>
<tr><td>T2</td><td>>0.9999</td><td>Ns</td></tr>
<tr><td>T3</td><td>>0.9999</td><td>Ns</td></tr>
<tr><td>T4</td><td>>0.9999</td><td>Ns</td></tr>
</table>

Abbreviations: PI = Plaque Index; EAP = erythritol-based air polishing; UPI = ultrasonic instrumentation with PEEK inserts; ns = not significant (p > 0.05); *Significance levels: *p < 0.05; **p < 0.01; ***p < 0.001; ****p < 0.0001.*

5.4.2. Subgroup distribution by prosthetic material

*5.4.2.1. **Descriptive analysis***

At baseline (T0), all subgroups exhibited high levels of plaque accumulation (Table 13). EAP-CER, EAP-ZIR, and EAP-DISIL showed mean values ranging from 67.5% to 70.0% (Table 13). Among the UPI subgroups, UPI-DISIL had the highest baseline mean (66.3%), followed by UPI-CER (56.3%) and UPI-ZIR (41.3%) (Table 13). In the following time points (T1 to T4), all subgroups demonstrated a progressive reduction in the Plaque Index (Table 13). In Groups EAP-CER, EAP-ZIR, and EAP-DISIL, the mean PI reached 0.00% as early as T3, maintaining this value at T4 (Table 13). A similar trend was observed in Group UPI-CER, where the index decreased steadily to 1.25% at T4. Group UPI-ZIR followed a comparable trend, reaching 2.50% at T4 (Table 13). Group UPI-DISIL showed the slowest decrease, with a residual mean of 3.75% at the final time point (Table 13). These results indicate a general reduction of dental plaque over time across all study subgroups, with some differences in the timing and completeness of the response depending on the treatment protocol applied.

Table 13. Descriptive analysis of Plaque Index (PI) in all subgroups.

Group	T0 Mean ± SD	T4 Mean ± SD	Δ
Group 1A EAP-CER	70.0 ± 25.1	0.0 ± 0.0	- 70.0
Group 1B EAP-ZIR	67.5 ± 23.1	0.0 ± 0.0	- 67.5
Group 1C EAP-DISIL	68.8 ± 22.8	0.0 ± 0.0	- 68.8
Group 2A UPI-CER	56.3 ± 19.7	1.25 ± 5.59	- 55.05
Group 2B UPI-ZIR	41.3 ± 31.7	2.5 ± 7.69	- 38.8
Group 2C UPI-DISIL	66.3 ± 24.7	3.75 ± 9.16	- 62.55

Abbreviations: PI = Plaque Index; SD = standard deviation; Δ = absolute mean difference between T0 and T4; EAP = erythritol-based air polishing; UPI = ultrasonic instrumentation with PEEK inserts; CER = feldspathic ceramic; ZIR = zirconia; DISIL = lithium disilicate.

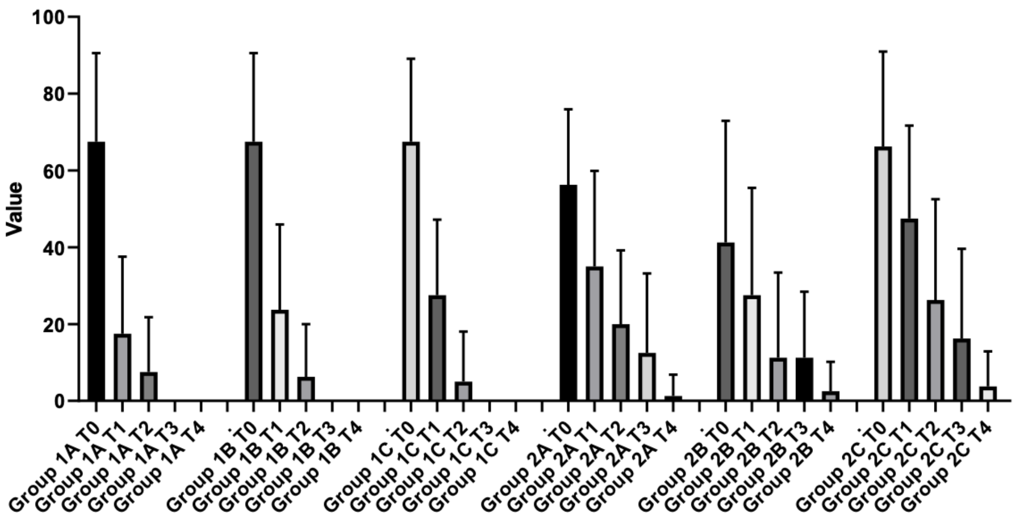

Figure 7. Temporal changes in Plaque Index (PI) in all subgroups

The figure illustrates a consistent downward trend in plaque accumulation across all subgroups, regardless of the restorative material. In the EAP-treated subgroups (1A–1C), the decline is steep and sustained, with complete plaque elimination (PI = 0%) achieved by T3 and maintained through T4, highlighting the rapid and uniform response to erythritol-based air polishing. The UPI subgroups (2A–2C) also show a progressive reduction in plaque levels, though with greater variability in both timing and extent. Notably, subgroup 2A (UPI–CER) follows a pattern similar to the EAP groups, reaching near-zero levels by the end of the follow-up. Subgroups 2B and 2C exhibit a more gradual decline, with slightly higher residual values at T4, particularly in the UPI–DISIL group, which shows the slowest resolution. Overall, while all subgroups demonstrate effective plaque control over time, the visual data suggest that erythritol-based treatment may lead to a faster and more complete reduction. However, plaque levels tend to converge toward minimal values in all groups by T4, supporting the clinical effectiveness of both protocols across different restorative materials (Figure 7).

5.4.2.2. *Inferential analysis*

The inferential analysis confirmed statistically significant reductions in Plaque Index (PI) values over time within all subgroups (Table 14). In particular, intra-group comparisons within the EAP-CER subgroup revealed significant differences from baseline to each follow-up time point, with adjusted p-values < 0.0001 from T2 onward, and p = 0.05 at T1. Similarly, the EAP-ZIR and EAP-DISIL subgroups showed highly significant reductions from baseline to T2, T3, and T4 (p < 0.0001) (Table 14). Significant intra-group differences were also observed in the UPI subgroups, especially UPI-CER and UPI-DISIL, with adjusted p-values ranging from 0.002 to < 0.0001 (Table 14).

Inter-group comparisons between EAP and UPI subgroups revealed no statistically significant differences at any timepoint (p > 0.9999), indicating similar baseline conditions and convergence in plaque control by the end of the follow-up (Table 14). These findings suggest that, despite different treatment modalities, all subgroups achieved comparably low plaque levels at T3 and T4 (Table 14).

Table 14. Dunn's multiple comparisons test of Plaque Index (PI) in all subgroups.

Intra-group comparisons (EAP subgroups)			
Subgroup	**Comparison**	**Adjusted p-value**	**Significance**
EAP-CER	**T0 vs T1**	0.05	**
	T0 vs T2	<0.0001	****
	T0 vs T3	<0.0001	****
	T0 vs T4	<0.0001	****
EAP-ZIR	**T0 vs T2**	<0.0001	****
	T0 vs T3	<0.0001	****
	T0 vs T4	<0.0001	****
EAP-DISIL	**T0 vs T2**	<0.0001	****
	T0 vs T3	<0.0001	****
	T0 vs T4	<0.0001	****
Intra-group comparisons (UPI subgroups)			

Subgroup	**Comparison**	**Adjusted p-value**	**Significance**
UPI-CER	**T0 vs T3**	0.002	**
	T0 vs T4	<0.0001	****
	T1 vs T4	0.033	*
UPI-ZIR	**T0 vs T4**	0.013	*
UPI-DISIL	**T0 vs T3**	0.006	**
	T0 vs T4	<0.0001	****
	T1 vs T4	0.003	**
Inter-group comparisons (EAP subgroups vs UPI subgroups)			
	Comparison	**Adjusted p-value**	**Significance**
EAP-CER vs UPI-CER	**T0**	>0.9999	Ns
	T1	>0.9999	Ns
	T2	>0.9999	Ns
	T3	>0.9999	Ns
	T4	>0.9999	Ns
EAP-ZIR vs UPI-ZIR	**T0**	>0.9999	Ns
	T1	>0.9999	Ns
	T2	>0.9999	Ns
	T3	>0.9999	Ns
	T4	>0.9999	Ns
EAP-DISIL vs UPI-DISIL	**T0**	>0.9999	Ns
	T1	>0.9999	Ns
	T2	>0.9999	Ns
	T3	>0.9999	Ns
	T4	>0.9999	Ns

Abbreviations: PI = Plaque Index; EAP = erythritol-based air polishing; UPI = ultrasonic instrumentation with PEEK inserts; CER = feldspathic ceramic; ZIR = zirconia; DISIL = lithium disilicate; ns = not significant ($p > 0.05$); *Significance levels*: *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$; ****$p < 0.0001$.

VI – DISCUSSION

VI -DISCUSSION

The present randomized clinical trial explored the long-term effectiveness of two distinct professional biofilm removal methods in the context of peri-implant maintenance: erythritol-based air polishing and ultrasonic instrumentation with PEEK-coated inserts. While several studies have previously investigated the efficacy of these approaches, this trial is among the few to provide a 24-month follow-up with a stratification based on prosthetic material. This comprehensive approach allowed not only a comparison of the two decontamination methods but also a reflection on their performance in relation to restorative substrates, providing an original contribution to the growing literature on individualized maintenance protocols in implantology.

One of the primary objectives of this study was to assess whether erythritol-based air polishing, known for its minimally abrasive properties and broad diffusion capacity, could offer a clinical advantage over ultrasonic instrumentation, particularly when combined with PEEK inserts. The effectiveness of such approaches is closely linked to the biological response of peri-implant tissues to implant surfaces, as well as to the influence of surface characteristics on biofilm behavior [Von Wilmowsky C et al., 2013; Kligman S et al., 2021]. The long-term follow-up was a key strength, enabling the observation of temporal trends and the consolidation of therapeutic effects over two years.

From a general perspective, both treatment protocols resulted in significant improvements in peri-implant parameters. Probing pocket depth (PPD), bleeding on probing (BoP), and plaque index (PI) all decreased over time in both groups, reflecting the effectiveness of regular non-surgical interventions. These findings are consistent with the current scientific consensus that underscores the importance of structured supportive therapy in maintaining peri-implant health and preventing disease progression [Herrera D et al., 2023; Berglundh T et al., 2018; Renvert S et al., 2018].

Nonetheless, while descriptive data suggested a more pronounced and rapid improvement in the erythritol group across all indices, inferential statistics did not reveal consistent significant differences between the two protocols. This discrepancy highlights a key interpretive challenge: the need to distinguish between clinical trends and statistically significant outcomes. For instance, the erythritol group showed an earlier and more homogeneous reduction in BoP and PI, which may translate into better patient perception and adherence, but this superiority was not always supported by robust statistical evidence.

The interpretation of these results must therefore be nuanced. It would be simplistic to claim the superiority of one method over the other solely on the basis of numerical reduction, particularly when differences fall within ranges that may not be clinically meaningful. For example, a 0.3 mm difference in mean PPD reduction, though statistically observable, may not influence clinical decision-making in patients with initially shallow pockets. Treatment choice must consider clinical feasibility, patient profile, and therapeutic goals, as emphasized by current decision-making models in mucositis management [Romito GA et al., 2024]

Moreover, these outcomes reflect a broader issue within peri-implant maintenance research: the multiplicity of variables affecting the effectiveness of decontamination protocols. This concept has been extensively addressed in the literature, highlighting the multifactorial etiology of peri-implantitis and the need for comprehensive prevention strategies [Smeets R et al., 2014]. These include patient compliance, implant geometry, prosthetic design, soft tissue phenotype, and operator variability—none of which can be fully controlled in clinical practice [Chankhore P et al, 2023]. In particular, implant positioning has been associated with variable risk for peri-implantitis development, further complicating outcome predictability [Song X et al., 2020]. As underlined by Ivanovski S et al. (2018), peri-implant soft tissue anatomy and its interaction with restorative elements are central to treatment outcomes and can mediate the response to non-surgical therapy [Ivanovski S et al., 2018].

In this trial, the absence of significant intergroup differences in cumulative analyses must also be considered in light of the relatively good baseline conditions of the enrolled patients. Most subjects presented with moderate indices, without severe inflammation or deep pockets, which likely limited the potential for differential improvement. This context is essential to correctly frame the results: in maintenance scenarios, where disease severity is limited, both protocols can be considered viable and safe, with treatment choice guided by other factors such as prosthetic design, patient sensitivity, and instrument accessibility. Future studies involving patients with more advanced peri-implant disease may yield different comparative results, as greater clinical variability could enhance the detection of treatment-specific effects.

Nonetheless, the more uniform improvements observed in the erythritol group may suggest a better suitability for complex prosthetic environments. Air polishing, due to its powder-based delivery and subgingival penetration, can reach interproximal and hard-to-access sites more effectively than ultrasonic inserts, especially in cases with multiple adjacent crowns or tight emergence profiles. This is supported by Louropoulou A et al. (2015), who demonstrated that air polishing leads to less surface damage while maintaining high biofilm removal efficacy [Louropoulou A et al., 2015].

Similarly, Jepsen S et al. (2015) and Delucchi F et al. (2025) advocate the use of erythritol-based air polishing as a safe and effective method for managing peri-implant mucositis, reinforcing its role in routine maintenance regimens. These authors emphasize not only the clinical performance of the method but also its patient-centered advantages, such as reduced discomfort and shorter treatment time, which may indirectly enhance compliance and long-term outcomes [Jepsen S et al., 2015; Delucchi F et al., 2025].

In addition to clinical findings, in vitro evidence supports the antimicrobial potential of erythritol powder. A study by Amate-Fernández F et al. (2021) demonstrated that erythritol-enriched powders significantly inhibited oral biofilm regrowth on implant surfaces, reducing bacterial viability and suggesting a preventive role in early biofilm control. These results provide a biological foundation for its use in supportive peri-implant therapy, especially in high-risk patients or during early disease phases [Amate-Fernández F et al., 2021].

Despite the lack of statistically significant superiority, the results obtained in the present study suggest that erythritol-based air polishing might offer relevant advantages in the clinical setting, particularly in terms of treatment homogeneity, patient comfort, and procedural safety. While ultrasonic instrumentation with PEEK tips remains a viable alternative and has demonstrated satisfactory outcomes in both BoP and PPD reduction, the air-polishing protocol seems to ensure a more predictable trajectory of improvement over time. This aspect acquires particular value in long-term maintenance, where the progressive accumulation of biofilm is inevitable and must be addressed with minimally invasive yet effective approaches.

Importantly, the findings of this trial should not be interpreted solely through the lens of absolute reductions in clinical indices, but rather in the broader context of individualized patient management. Contemporary approaches to peri-implant maintenance emphasize the importance of individualized protocols, shaped by the patient's previous disease experience, the anatomical and prosthetic challenges of each case, and the need to ensure both mechanical efficacy and long-term patient adherence [Perussolo J et al., 2024]. Within this paradigm, erythritol-based air polishing offers characteristics—such as low abrasiveness, greater reach in subgingival areas, and better patient perception [Gheorghe DN et al., 2023]—that justify its selection even in the absence of statistically demonstrable superiority.

Several authors have emphasized these multidimensional aspects of peri-implant care. Ivanovski S et al. 2018 described how marginal tissue architecture around implants can differ significantly from that of natural teeth, affecting the progression of inflammation and the efficacy of decontamination techniques. The presence of parallel collagen fibers, absence of a periodontal ligament, and reduced vascularity make peri-implant tissues particularly vulnerable to bacterial insult and mechanical trauma [Ríos-Osorio N et al., 2025]. Hence, decontamination protocols must be effective yet atraumatic—criteria that erythritol-based air polishing tends to fulfill better than more abrasive or rigid instrumentation [Delucchi F et al., 2025; Hentenaar DFM et al, 2022].

Furthermore, the role of prosthetic materials in influencing peri-implant outcomes remains an area of active research. In this trial, patients were stratified based on three restorative materials—feldspathic ceramic, zirconia, and lithium disilicate—in order to explore whether the interaction between surface characteristics and decontamination methods affected clinical outcomes. While no statistically significant differences emerged among the subgroups, the stratified analysis confirmed that both air polishing and ultrasonic instrumentation were effective across all materials. These findings are in line with those of Berglundh T et al. (2018), who reported that the nature of the prosthetic material may influence microbial adhesion and tissue response but does not necessarily require protocol-specific decontamination if regular maintenance is performed [Berglundh T et al., 2018].

Nevertheless, certain trends were observed that merit clinical attention. In subgroups treated with air polishing, particularly those with lithium disilicate and feldspathic ceramic restorations, improvements in PI and BoP occurred earlier and with greater uniformity. This could reflect a better adaptation of air-polishing particles to smoother and more fragile surfaces, minimizing surface alterations and enhancing debridement in difficult-to-access zones. These tendencies are coherent with the findings of Louropoulou A et al. (2015), who demonstrated that air polishing was associated with the lowest degree of surface alteration on implant and abutment materials, and with reduced iatrogenic damage compared to ultrasonic tips [Louropoulou A et al., 2015].

This aligns with previous findings indicating that BoP reduction is a key parameter in peri-implant health improvement, as it reflects a decrease in microbial-induced tissue inflammation [Monje A et al., 2016]. Similarly, when evaluating bleeding on probing across subgroups, all prosthetic materials demonstrated a clear improvement over time. While some variations were observed in the initial response to treatment, the long-term reduction in inflammation remained comparable, highlighting the reliability of both approaches in maintaining peri-implant soft tissue health. The fact that no significant intergroup differences were observed suggests that mechanical disruption of the biofilm, rather than the specific instrument used, is the determining factor in reducing inflammation. These findings further validate the role of professional maintenance therapies in preventing the progression of peri-implant mucositis to peri-implantitis, which remains a major concern in implant dentistry [Schwarz F et al., 2015].

Plaque accumulation is one of the primary etiological factors in peri-implant disease, making its control a fundamental aspect of long-term implant maintenance. The significant reduction in PI observed in both groups highlights the effectiveness of both approaches in controlling biofilm accumulation. Previous studies have also demonstrated the efficacy of air-abrasive debridement with glycine powder as a viable alternative for peri-implant maintenance, showing comparable results to mechanical debridement and chlorhexidine administration over a six-month period [Gheorghe DN et al., 2023]. Although the erythritol group exhibited slightly lower PI values at each time point, patient compliance and comfort may have played a role in this trend. Plaque control followed the same pattern across different prosthetic materials, with both treatment modalities contributing effectively to biofilm removal. The similarities between subgroups further suggest that successful plaque management is primarily linked to the mechanical decontamination approach rather than the specific prosthetic material used. Air-polishing with erythritol has been reported to be more comfortable and less invasive compared to ultrasonic instrumentation, which may contribute to better patient adherence to maintenance recommendations [Brunello G et al., 2020]. Previous studies have suggested that the perception of comfort during professional hygiene procedures can influence patient motivation and compliance, which in turn affects the long-term success of implant maintenance strategies [Leone FD et al., 2024; Monje A et al., 2016].

Another consideration relates to the long-term stability of clinical parameters. Over the 24-month period, patients in the erythritol group maintained low values of PI and BoP with minimal fluctuation, suggesting a stabilizing effect of this method when included in regular recall protocols. These results are in line with previous research demonstrating that non-surgical interventions, particularly air-polishing—and, in some studies, ultrasonic debridement—are essential in preventing disease progression and promoting tissue healing [Luengo F et al., 2023; Schwarz et al., 2015]. Additionally, the consistent improvement in PPD across all follow-up periods suggests that regular professional maintenance sessions play a pivotal role in sustaining peri-implant health over time [Rösing CK et al., 2019]. The importance of maintenance therapy in preventing peri-implantitis is well established, as shown by Renvert et al. (2018), who underscored the role of repeated non-surgical interventions in prolonging implant survival. In this regard, treatment protocols that support better biofilm control and foster greater patient acceptance may contribute not only to short-term improvements but also to the long-term success of implant-supported rehabilitation [Renvert S et al., 2018].

Moreover, recent studies have begun to emphasize the immunological impact of decontamination methods on peri-implant tissues. The modulation of the local inflammatory response, rather than mere mechanical removal of plaque, is emerging as a critical component of successful therapy. Herrera et al. (2023) and Apaza-Bedoya K et al. (2024) noted that repeated mechanical trauma or residual biofilm can perpetuate low-grade inflammation, which may remain subclinical for long periods before manifesting as tissue breakdown [Herrera D et al., 2023; Apaza-Bedoya K et al., 2024]. In this light, low-impact protocols such as air polishing could theoretically reduce chronic stimulation of peri-implant immune cells, favoring mucosal homeostasis [Schwarz F et al., 2015]. While this hypothesis was not directly tested in the present study, it offers a compelling explanation for the clinical trends observed, and merits further exploration.

Another aspect worth emphasizing concerns the operational characteristics of the two instruments compared. The PEEK-coated ultrasonic inserts were selected to mitigate the risk of surface damage traditionally associated with metallic tips. PEEK (polyether ether ketone) has been widely recognized for its biocompatibility and mechanical resilience, making it a favorable option for peri-implant instrumentation [Moharil S et al., 2023]. However, the rigidity of ultrasonic tips, even when PEEK-coated, may limit their effectiveness in decontaminating intricate areas, particularly in patients with complex prosthetic configurations or subgingival niches [Schmage P et al., 2019; Cha JK et al., 2019]. In contrast, erythritol-based air polishing, with its fine particle size and dynamic flow properties, adapts more flexibly to different implant geometries and soft tissue contours, enhancing the likelihood of thorough debridement in difficult-to-reach areas [Liu CC et al., 2024; Delucchi F et al., 2025; Clementini M et al., 2023].

The relevance of this characteristic becomes especially pronounced when dealing with full-arch restorations or cases involving closely spaced implants, where mechanical access is compromised [Yang J et al., 2021]. In such scenarios, the capacity of air-polishing devices to uniformly disperse the powder and maintain efficacy with minimal mechanical contact is an invaluable advantage. This reflects the evolving paradigm in peri-implant maintenance that favors minimally invasive, tissue-friendly techniques over force-dependent approaches [Gheorghe DN et al., 2023; Corbella S et al., 2024]. The superiority of air polishing in accessing these regions has been reported by Louropoulou A et al. (2015) and more recently validated by Delucchi F et al. (2025), who demonstrated its efficacy in plaque removal even in anatomically constrained zones [Louropoulou A et al., 2015; Delucchi F et al., 2025].

Furthermore, beyond technical efficacy, patient comfort and perceived invasiveness of the procedure are emerging as pivotal determinants of treatment acceptance and adherence to maintenance programs. Several studies have shown that air polishing is associated with reduced discomfort, shorter chair time, and lower post-treatment sensitivity compared to ultrasonic scaling [Gheorghe DN et al., 2023; Liu CC et al., 2024]. This may not directly influence clinical outcomes, but it plays a substantial role in long-term compliance, which is essential for the prevention of disease recurrence [Rösing CK et al., 2019]. In this trial, although patient-reported outcomes were not formally assessed, the clinical operators consistently observed higher acceptance and ease of implementation with the erythritol-based approach. These anecdotal insights align with prior findings and should be considered when designing patient-centered maintenance strategies [Jepsen S et al., 2015; Liu CC et al., 2024; Gheorghe DN et al., 2023; Clementini M et al., 2023].

It is also important to reflect on the temporal dynamics of clinical improvement. The results demonstrated that most of the clinical benefits occurred during the first 6–12 months, with a plateau in both PPD and PI values from T3 to T4. This pattern suggests that the most significant tissue responses to professional decontamination occur early during the recall period, and that sustaining those improvements depends more on consistency than on the intensity of subsequent treatments. This reinforces the concept of supportive peri-implant therapy as a repetitive, preventive intervention rather than a corrective one. In this context, choosing a method that is both effective and repeatable with minimal risk of cumulative trauma becomes critical—again favoring approaches like erythritol air polishing [Frisch E et al., 2020].

The role of prosthetic materials, although not statistically significant in this study, warrants further attention. Despite the absence of meaningful inter-subgroup differences, trends observed suggest that certain restorative substrates may interact differently with the biofilm or respond differently to decontamination efforts. For instance, feldspathic ceramics and lithium disilicate, with their smoother and less retentive surfaces [Hussein AI et al., 2016; Topçu S et al.,2024], might facilitate easier plaque removal, as suggested by the slightly faster improvements observed in the erythritol-treated subgroups. Conversely, zirconia, while biocompatible and commonly used, has been reported to exhibit a higher bacterial affinity under some conditions [Topçu S et al.,2024], potentially requiring more aggressive or frequent interventions. These hypotheses remain speculative in the absence of microbiological data, but they open the door for future research investigating the interplay between prosthetic materials and maintenance protocols.

Lastly, this study contributes to a growing understanding that peri-implant disease prevention is not solely a function of the chosen decontamination tool, but rather the result of a coordinated strategy involving prosthetic planning, patient education, professional maintenance, and individualized recall intervals [Perussolo J et al., 2024]. The high success rates observed in both groups suggest that when a structured, standardized protocol is followed, the specific method of debridement may be of secondary importance compared to the overall quality and consistency of care. Nevertheless, the subtle advantages observed with erythritol-based air polishing—especially in terms of treatment homogeneity, surface preservation, and user-friendliness—position it as a compelling choice in modern implant maintenance, particularly for patients with high aesthetic demands, sensitive tissues, or multiple prosthetic elements [Delucchi F et al., 2025].

Beyond the direct comparison of the two decontamination protocols, the present findings contribute to a broader understanding of peri-implant maintenance as a dynamic and patient-tailored process. In modern implantology, it is increasingly recognized that the success of maintenance therapy depends not only on the mechanical efficacy of the instruments used, but also on the integration of multiple variables, including patient risk profile, implant anatomy, and prosthetic complexity [Chankhore P et al., 2023; Guarnieri R et al, 2023]. The individualized stratification adopted in this study, based on prosthetic material, exemplifies this personalized approach and reflects the clinical need to move away from standardized recall strategies toward more nuanced, risk-adapted models. The long-term success of peri-implant maintenance strategies, as highlighted by this study, appears to rely not only on the biofilm removal capacity of the instruments, but also on patient-related factors such as systemic conditions, compliance, and the complexity of the prosthetic design [Araújo TG et al., 2024; Guarnieri R et al., 2023;]. This paradigm shift is supported by contemporary literature emphasizing risk assessment and preventive maintenance as cornerstones of peri-implant care. The concept of the "vulnerable patient," often defined by reduced dexterity, limited access, or high plaque retention, requires interventions that are not only effective but also well-tolerated and minimally traumatic [Gheorghe DN et al. 2023; Brunello G et al., 2020; Leone FD et al., 2024]. Erythritol-based air polishing aligns well with these needs, offering a balance between efficacy and tissue preservation, particularly for patients with a history of mucositis or in cases where iatrogenic damage could compromise aesthetic outcomes [Brunello G et al., 2020; Leone FD et al., 2024].

In contrast, the use of ultrasonic instrumentation—while clinically effective [Liu CC et al., 2024; Delucchi F et al, 2025; Hentenaar DFM et al., 2022]—may pose greater challenges in terms of comfort, accessibility, and surface wear, especially in posterior regions or in patients with limited mouth opening [Jepsen S et al., 2015]. Although the PEEK coating mitigates the abrasive potential of conventional metal tips, it does not eliminate the limitations inherent to rigid debridement methods. These differences, while subtle, may accumulate over time and influence long-term treatment success and patient compliance [Louropoulou A et al., 2015; Schmage P et al., 2014].

It is also worth noting that the study did not investigate alternative adjunctive strategies, such as antimicrobial photodynamic therapy, topical chlorhexidine gels, or ozone therapy, all of which have shown promise in enhancing biofilm disruption and modulating the host response [Herrera D et al., 2023; Dumitriu AS et al., 2023;

Huang S et al., 2023; Scribante A et al., 2024]. However, many of these approaches suffer from limited accessibility, higher cost, or insufficient standardization, making them less suitable for routine maintenance [Derks J et al., 2023]. In contrast, both tested protocols in this trial are reproducible, scalable, and compatible with general clinical practice, thus ensuring a high degree of external validity.

Importantly, the consistency of the results across different prosthetic materials reinforces the notion that regular decontamination—regardless of the technique—is fundamental to controlling inflammation. This observation supports the recommendations of recent EFP consensus reports, which emphasize the central role of professional hygiene in preventing peri-implantitis [Herrera D et al., 2023; Jepsen S et al., 2015]. Nonetheless, the added benefits of air polishing in terms of reach, comfort, and surface integrity make it particularly advantageous in high-risk patients or those requiring long-term recall programs [Delucchi F et al., 2025].

The integration of immunological insights into peri-implant therapy represents another emerging frontier that may further clarify the advantages of minimally invasive protocols. As highlighted by Apaza-Bedoya et al. (2024), chronic low-grade inflammation in peri-implant tissues is not solely a function of biofilm load, but also of the host's inflammatory threshold and mucosal resilience [Apaza-Bedoya K et al., 2024]. Techniques that minimize tissue trauma while achieving sufficient microbial control could theoretically reduce the cyclical nature of inflammation, promoting tissue homeostasis and reducing the risk of progression to peri-implantitis [Assery NM et al. 2023; Brunello G et al. 2020; Yang J et al., 2021]. Although not explicitly measured in this trial, the stable BoP and PI values observed in the erythritol group may reflect such immunomodulatory effects, warranting further investigation in future research incorporating cytokine profiling or microbiome analysis.

Finally, from a clinical standpoint, the choice of maintenance protocol should not be isolated from the broader therapeutic context. Factors such as time efficiency, operator fatigue, equipment availability, and economic considerations all play a role in shaping practice patterns [Perussolo J et al., 2024; Liu CC et al., 2024; Butera A et al, 2022]. In this sense, air polishing may offer logistical advantages due to its rapid application, reduced instrument wear, and lower need for extensive training. While these aspects were not formally evaluated in the present study, they contribute to the real-world feasibility and scalability of the approach, especially in multidisciplinary or high-volume clinical settings [Liu CC et al., 2024; Delucchi F et al., 2025; Butera A et al, 2022].

The plateau observed in clinical indices between the 12- and 24-month follow-ups raises relevant questions about the temporal dynamics of peri-implant tissue response and the optimal scheduling of maintenance interventions. Both treatment groups demonstrated the majority of their clinical improvement during the first year, with minimal changes thereafter. This pattern is consistent with other longitudinal studies and suggests that while initial decontamination plays a key role in resetting the inflammatory baseline, long-term tissue stability depends more on the consistency and appropriateness of maintenance than on incremental intensification of treatment [Monje A et al., 2016; Leone FD et al., 2024; Rösing CK et al., 2019].

This observation aligns with the notion that supportive peri-implant therapy should focus not on escalation, but on consolidation. Once inflammation is brought under control, the challenge becomes maintaining homeostasis with the least invasive and most sustainable approach. From this perspective, erythritol-based air polishing presents a strong case. Its low mechanical impact, ease of use, and favorable patient perception make it particularly suited for repeated application without inducing cumulative trauma or desensitization [Jepsen S et al., 2015; Delucchi F et al, 2025; Gheorghe DN et al., 2023; Brunello G et al., 2020]. This is especially relevant in aesthetic zones or in patients with thin mucosal biotypes, where repeated instrumentation with rigid inserts may increase the risk of recession, bleeding, or marginal inflammation over time [Araújo TG et al. 2024; da Silva DM et al., 2025].

Moreover, the minimal fluctuation in BoP and PI scores seen in the erythritol group during the second year of follow-up may suggest a stabilization of the peri-implant microenvironment—a clinical manifestation of sustained immune modulation and effective plaque control. While these results should be interpreted cautiously, given the absence of direct immunological or microbiological markers, they echo findings from studies exploring low-impact therapies and their ability to maintain epithelial integrity and mucosal resilience over time [Jepsen S et al., 2015; Delucchi F et al., 2025; Gheorghe DN et al., 2023; Hentenaar DFM et al., 2022].

This has important implications for designing patient-specific maintenance schedules. Rather than applying uniform recall intervals to all implant patients, clinicians may benefit from tailoring the frequency and intensity of interventions based on the observed response to early therapy. Patients who achieve stable parameters within the first year—particularly under low-impact protocols—may not require as frequent instrumentation, thereby reducing chair time, patient burden, and potential soft tissue damage. In this context, erythritol air polishing could serve as a valuable "baseline therapy," to be modulated depending on disease history, plaque control ability, and prosthetic architecture [Herrera D et al., 2023; Jepsen S et al., 2015; Delucchi F et al., 2025; Brunello G et al., 2020; Leone FD et al., 2024.

Furthermore, in full-arch rehabilitations, or in complex rehabilitations combining natural teeth and implants, the integration of a low-abrasion modality like erythritol air polishing offers logistical and clinical benefits [Yang J et al., 2021]. Its flexibility and safety profile allow for seamless transitions across different surfaces without the need for multiple instruments or handpiece changes. This can streamline workflows and improve consistency of care, particularly in settings with limited access to specialized equipment or operators with varied levels of experience [Liu CC et al., 2024; Delucchi F et al., 2025].

Finally, the results of this trial reinforce a growing consensus that modern peri-implant maintenance should not be conceptualized merely as mechanical cleaning, but rather as a therapeutic continuum rooted in prevention, tissue preservation, and patient-centeredness. The choice of instrumentation, therefore, becomes a reflection of broader treatment values: efficacy, safety, comfort, and respect for biological integrity [Herrera D et al., 2023; Liu CC et al., 2024]. While both protocols tested in this study demonstrated effectiveness, the additional benefits associated with erythritol-based air polishing—though subtle and sometimes statistically non-significant—align well with this contemporary vision of care and justify its broader implementation in clinical routines.

A further dimension that deserves attention is the biological behavior of peri-implant biofilm over time, particularly in relation to chronicity and resistance to mechanical removal. It is increasingly acknowledged that long-standing biofilm formations can adopt a more resilient structure, incorporating extracellular polymeric substances and creating anaerobic microenvironments that shield pathogens from both mechanical disruption and host immune surveillance [Amate-Fernández P et al., 2021]. This biological complexity underlines the importance of early intervention and frequent decontamination in the subclinical phase of peri-implant disease. When biofilm is left undisturbed for extended periods, its physical removal becomes more challenging, and adjunctive therapies may be less effective [Gheorghe DN et al., 2023]. The modest but consistent improvements observed in both groups of this study, especially during the early follow-up phases, reinforce the rationale for proactive rather than reactive maintenance protocols [Monje A et al., 2016].

In this regard, the potential of erythritol-based air polishing to interfere with biofilm maturation and reorganization merits particular emphasis [Amate-Fernández P et al., 2021]. By disrupting microbial communities at an earlier stage and with less mechanical stress, air polishing may prevent the establishment of pathogenic niches that later require more aggressive interventions [Delucchi F et al., 2025]. Although not directly assessed in the present study, future research focusing on biofilm architecture, microbial composition, and inflammatory mediators before and after treatment could provide deeper insights into this preventive mechanism [Gheorghe DN et al., 2023]. The translational value of such findings would be considerable, especially in redefining maintenance intervals and instrument selection according to biofilm dynamics rather than static clinical indices [Leone FD et al., 2024; Yang J et al., 2021; Guarnieri R et al., 2023].

A comparative reflection on alternative adjunctive therapies is also pertinent. In recent years, techniques such as antimicrobial photodynamic therapy (aPDT), diode and Er:YAG laser decontamination, and ozone-based modalities have been proposed as complementary or even substitute approaches to conventional maintenance [Huang S et al., 2022; Scribante A et al., 2023]. While in vitro and pilot clinical studies have shown some promising results in reducing bacterial loads and inflammatory markers, their clinical utility remains controversial [Huang S et al., 2022; Scribante A et al., 2023; Butera A et al., 2022]. Limitations include the high cost of equipment, the need for specific operator training, variability in protocols, and inconsistent long-term outcomes [Huang S et al., 2022; Butera A et al., 2022]. Moreover, these approaches often lack the mechanical disruption component necessary for removing mature deposits and calculus, thereby restricting their use to specific clinical scenarios [Louropoulou A et al., 2015; Delucchi F et al., 2025]. In contrast, both erythritol air polishing and ultrasonic instrumentation are widely available, require minimal additional training, and can be integrated into routine workflows with predictable outcomes [Jepsen S et al., 2015; Delucchi F et al., 2025; Schmage P et al., 2014]. Their reproducibility and scalability thus offer a clear advantage in real-world settings, particularly in general dental practices with limited resources [Jepsen S et al., 2015; Perussolo J et al., 2024; Delucchi F et al., 2025].

Another point worth elaborating is the clinical significance of the therapeutic plateau observed between the 12- and 24-month timepoints. This temporal trend, also reported in other longitudinal studies, suggests that while the initial phase of maintenance therapy is characterized by notable improvements in clinical indices, the subsequent period is more about stabilization than progression [Delucchi F et al., 2025; Monje A et al., 2016; Rösing CK et al., 2019]. The implications of this finding are multifaceted. On one hand, it supports the hypothesis that supportive therapy serves primarily as a preventive measure to preserve established gains, rather than as a curative strategy [Jepsen S et al., 2015; Herrera D et al., 2023]. On the other, it challenges the conventional notion that intensified instrumentation is always beneficial in the long term [Schwarz F et al., 2015]. Excessive or overly frequent mechanical debridement—particularly with abrasive tools—may actually harm soft tissues and reduce patient compliance without providing additional therapeutic benefit [Louropoulou A et al., 2015; Kochar SP et al., 2022]. From this perspective, the low-impact nature of air polishing gains further value, offering a means to maintain peri-implant health with minimal biological cost and high patient acceptance [Delucchi F et al., 2025; Clementini M et al., 2023].

While this study focused on non-surgical maintenance, evidence from surgical contexts is also relevant when assessing the broader applicability of erythritol-based air polishing. In a randomized controlled trial by Hentenaar et al.

(2022), the adjunctive use of erythritol air polishing during access flap surgery for peri-implantitis did not lead to significantly better outcomes compared to surgery alone [Hentenaar DFM et al., 2022]. Although both groups improved clinically, the lack of statistical differences in probing depth reduction or bleeding on probing suggests that the benefits of erythritol may be more pronounced in preventive or early-intervention settings rather than as a curative tool in advanced disease [Hentenaar et al., 2022]

Logistical and economic considerations also come into play when selecting maintenance protocols, especially in the context of multidisciplinary and high-volume practices [Rösing CK et al., 2019]. Instruments that are quick to deploy, easy to maintain, and compatible with a wide range of prosthetic and implant configurations provide a distinct advantage [Delucchi F et al., 2025]. Erythritol-based air polishing systems, once the initial investment is made, tend to have lower per-treatment costs due to reduced consumable wear and faster treatment times [Liu CC et al., 2024]. Furthermore, the intuitive application technique makes them suitable for delegation to trained hygienists or dental auxiliaries, thereby optimizing clinical efficiency [Clementini M et al., 2023]. These factors, while secondary to clinical efficacy, significantly influence the scalability and sustainability of maintenance programs—particularly in public health systems or large clinics serving diverse populations [Jepsen S et al., 2015; Rösing CK et al., 2019].

The discussion would not be complete without reiterating the centrality of patient perception in shaping the long-term success of implant therapy [Brunello G et al., 2020]. As dentistry increasingly embraces a patient-centered model, factors such as comfort, procedure duration, and post-treatment sensitivity acquire clinical importance alongside conventional indices like BoP and PI [Jepsen S et al., 2015; Clementini M et al., 2023]. In the present study, although patient-reported outcomes were not formally assessed, clinical operators noted higher acceptance and perceived tolerability with the erythritol protocol. These anecdotal observations echo findings from multiple surveys and clinical trials, which report superior patient satisfaction with air polishing compared to ultrasonic scaling [Delucchi F et al., 2025; Corbella S et al., 2024; Brunello G et al., 2020]. In the long run, such perceptions can affect not only compliance with maintenance schedules but also patient loyalty, satisfaction with treatment, and overall quality of life [Leone FD et al., 2024].

Ultimately, the findings of this study highlight the complexity and multidimensionality of peri-implant maintenance [Herrera D et al., 2023; Renvert S et al., 2015]. No single tool or protocol can be universally optimal, and clinical decisions must be tailored to the unique anatomical, prosthetic, immunological, and behavioral characteristics of each patient [Kochar SP et al., 2022; Guarnieri R et al., 2023; Araújo TG et al., 2024]. Within this individualized framework, erythritol-based air polishing emerges not as a replacement for ultrasonic instrumentation, but as a highly effective, safe, and patient-friendly option that aligns well with contemporary therapeutic goals [Jepsen S et al., 2015; Liu CC et al., 2024; Delucchi F et al., 2025]. Its integration into regular maintenance routines—especially for patients at higher aesthetic risk, with multiple prosthetic units, or presenting with early signs of mucosal inflammation—represents a rational and evidence-supported approach to long-term implant success [Corbella S et al., 2024; Brunello G et al., 2020; Leone FD et al., 2024].

VII – CONCLUSIONS

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This randomized clinical trial aimed to evaluate the long-term effectiveness of two non-surgical biofilm decontamination protocols—erythritol-based air polishing and ultrasonic instrumentation with PEEK-coated tips—during peri-implant maintenance therapy. A total of 120 patients were followed over a 24-month period, with stratification by prosthetic material to explore the influence of restorative surfaces on treatment efficacy.

Both interventions proved clinically effective in improving peri-implant parameters, with significant reductions in probing pocket depth (PPD), bleeding on probing (BoP), and plaque index (PI) across the entire sample. Over time, both protocols resulted in favorable clinical outcomes, without statistically significant differences between them at the final follow-up.

Although inferential analyses did not demonstrate the statistical superiority of one protocol over the other, the erythritol-based air polishing group exhibited a more consistent trend of early improvements, particularly in BoP and PI. While these observations were not supported by statistically significant intergroup differences, they may still hold clinical relevance in certain scenarios, especially when considering treatment accessibility and patient-related factors.

Furthermore, subgroup analyses revealed that the observed clinical improvements were consistent across all restorative materials. No statistically significant interactions were found between the type of prosthetic crown (feldspathic ceramic, zirconia, or lithium disilicate) and the clinical outcomes, indicating that the efficacy of both protocols was independent of the restorative surface. This further supports the generalizability of the findings across different implant-supported prosthetic configurations.

Overall, both approaches were effective and safe. However, the more uniform clinical trajectory observed in the erythritol group suggests that minimally invasive methods may offer added value in preserving peri-implant health over time. These findings reinforce the importance of regular professional maintenance and support the integration of individualized protocols that take into account prosthetic design, patient risk profile, and treatment tolerability.

In light of the study results, the null hypothesis was not rejected, as no statistically significant differences were found between the two treatment protocols over the 24-month observation period. Despite this, both groups exhibited significant clinical improvements in the intragroup analysis, underscoring the central role of mechanical biofilm disruption in peri-implant maintenance. These outcomes suggest that the success of professional decontamination strategies is primarily dependent on the consistency and quality of biofilm removal, rather than on the specific technique employed.

VIII – LIMITATIONS AND FUTURE WORK

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When critically evaluating the results obtained, it is necessary to acknowledge several methodological limitations that characterize the present study. Firstly, being a single-center study, the generalizability of the data may be limited by the specific clinical setting and the characteristics of the recruited population. Organizational, logistical, and clinical features of the reference center may have influenced protocol adherence, recall management, or clinical interpretation, thus reducing the applicability of the findings to different settings.

Another point of concern lies in the absence of operator blinding, which may have introduced performance bias, although this was partially mitigated by the use of standardized and objective clinical measurements. Furthermore, the lack of microbiological or biochemical assessments constitutes a relevant limitation, as it prevents a deeper understanding of the biological mechanisms underlying treatment effectiveness. The absence of data regarding the evolution of the peri-implant microbiota or the local immune response makes it impossible to determine whether the observed clinical improvements correspond to actual reductions in pathogen load or inflammatory modulation.

From the perspective of patient selection, the study did not exclude individuals with systemic conditions known to interfere with peri-implant health, such as diabetes or smoking. While this increases external validity and better reflects the complexity of daily clinical practice, it also introduces confounding variables that are difficult to control and may have affected tissue responses regardless of the decontamination protocol adopted.

In addition, data on implant and prosthetic crown placement timing were not collected—information that could be relevant, since implant age may influence tissue stability and responsiveness to maintenance therapy. Although all patients were enrolled in regular hygiene programs, variability in implant history represents a factor that deserves more attention in future investigations.

Another limitation concerns the management of home oral hygiene, which was neither standardized nor monitored during the follow-up period. Compliance was assessed based on attendance at scheduled maintenance visits but without any direct evaluation of personal hygiene behavior. This introduces a potential confounder, as the success of professional maintenance is closely linked to effective self-care, and undetected inter-individual differences may have influenced clinical outcomes.

The lack of patient-reported outcomes—such as perceived comfort, satisfaction, or treatment preference—also represents a significant limitation. In the context of long-term maintenance, where adherence to recall visits is essential for success, subjective aspects related to the patient experience become increasingly important for therapeutic decision-making and long-term sustainability. Including these dimensions in future studies would contribute to making peri-implant maintenance protocols more patient-centered and clinically applicable.

Based on these considerations, future research should aim for multicenter trials conducted on larger and more diverse populations, with extended follow-up periods. The implementation of innovative tools, including microbiological assessments, inflammatory biomarker analysis, integrated digital applications, and AI-based software, may help clarify the biological mechanisms behind peri-implant disease progression and treatment response.

It will also be essential to investigate the combined effectiveness of different adjunctive approaches, such as non-pharmacological decontamination techniques, ozone therapy, and photobiomodulation. Exploring these strategies in high-risk populations—such as smokers, diabetic patients, or those with a history of mucositis or peri-implantitis—could offer crucial insights for optimizing maintenance protocols in complex clinical scenarios. Understanding how these interventions perform in challenging conditions will not only refine treatment selection criteria but also contribute to the development of increasingly precise, evidence-based guidelines for long-term implant maintenance.

IX – BIBLIOGRAPHICAL REFERENCES

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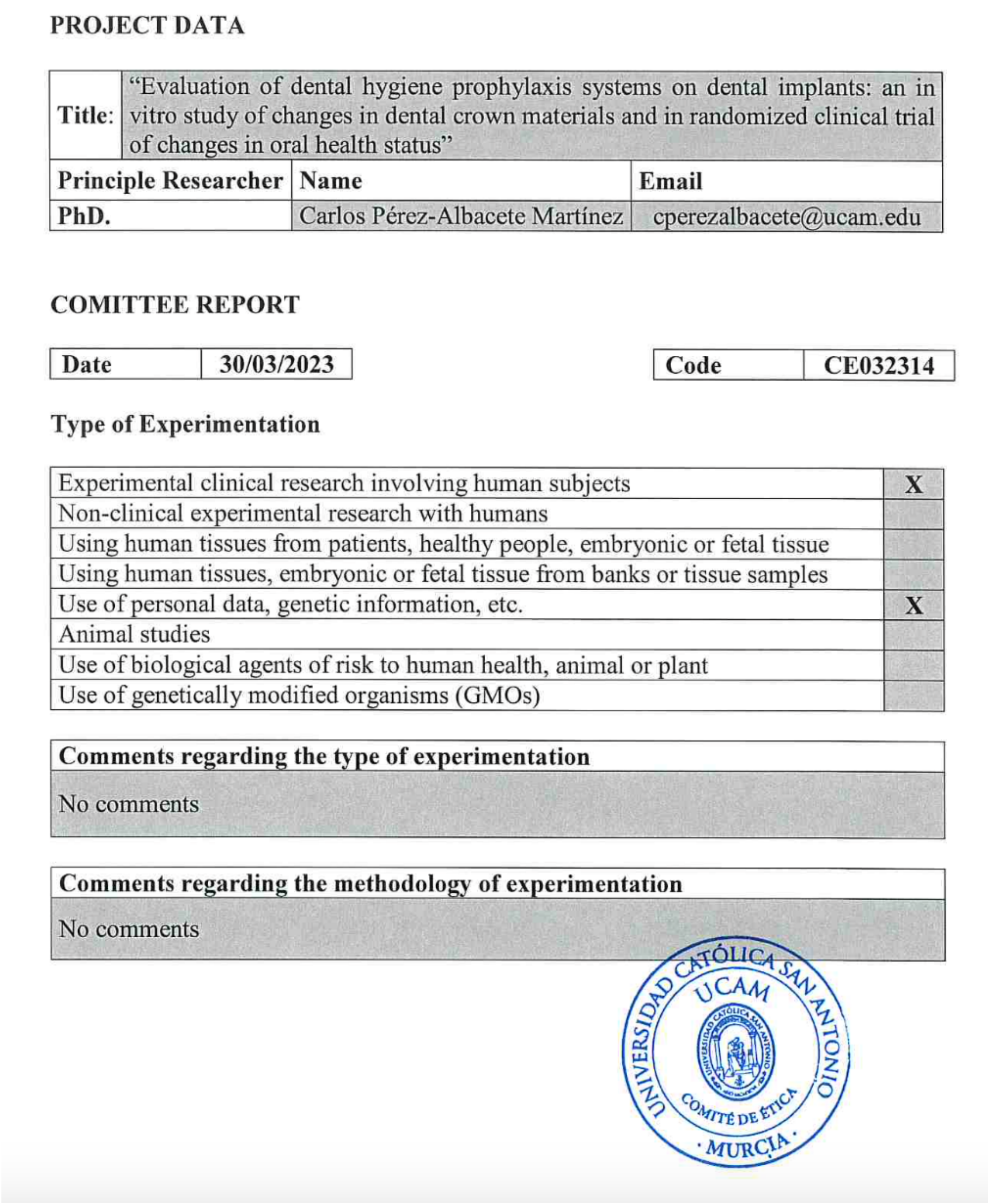
X – APPENDIXES

X - APPENDIXES

Appendix 1. UCAM Approval Ethics Committee



PROJECT DATA

Title:	"Evaluation of dental hygiene prophylaxis systems on dental implants: an in vitro study of changes in dental crown materials and in randomized clinical trial of changes in oral health status"	
Principle Researcher	**Name**	**Email**
PhD.	Carlos Pérez-Albacete Martínez	cperezalbacete@ucam.edu

COMITTEE REPORT

Date	**30/03/2023**	**Code**	**CE032314**

Type of Experimentation

Experimental clinical research involving human subjects	**X**
Non-clinical experimental research with humans	
Using human tissues from patients, healthy people, embryonic or fetal tissue	
Using human tissues, embryonic or fetal tissue from banks or tissue samples	
Use of personal data, genetic information, etc.	**X**
Animal studies	
Use of biological agents of risk to human health, animal or plant	
Use of genetically modified organisms (GMOs)	

Comments regarding the type of experimentation
No comments

Comments regarding the methodology of experimentation
No comments

Appendix 2. UCAM Approval Ethics Committee

UCAM
UNIVERSIDAD CATÓLICA
SAN ANTONIO

UCAM ETHICS COMMITTEE

Suggestions for the researcher

In view of the application of the attached report by the Researcher and the above mentioned recommendations, the opinion of the Committee is to:

Issue a favorable report	X
Issue an unfavorable report	
Issue a favorable report with subject to correction	

MOTIVATION
It will increase knowledge in this area

Approved by the President,

Sig.: José Alberto Cánovas Sánchez

Approved by the Secretary,

Sig.: José Alarcón Teruel

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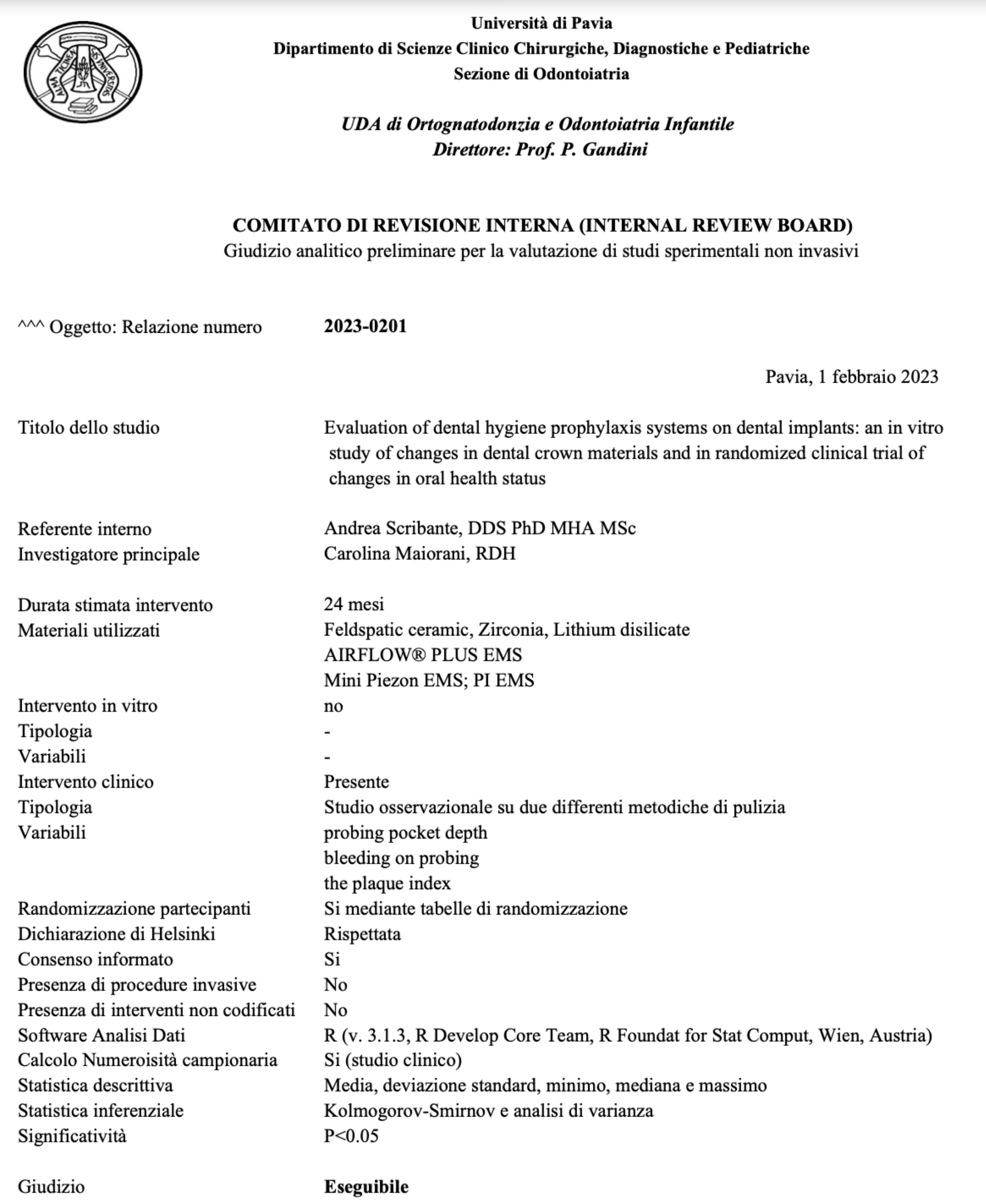
Appendix 3. UNIPV Approval Ethics Committee



Università di Pavia
Dipartimento di Scienze Clinico Chirurgiche, Diagnostiche e Pediatriche
Sezione di Odontoiatria

UDA di Ortognatodonzia e Odontoiatria Infantile
Direttore: Prof. P. Gandini

COMITATO DI REVISIONE INTERNA (INTERNAL REVIEW BOARD)
Giudizio analitico preliminare per la valutazione di studi sperimentali non invasivi

^^^ Oggetto: Relazione numero **2023-0201**

Pavia, 1 febbraio 2023

Titolo dello studio	Evaluation of dental hygiene prophylaxis systems on dental implants: an in vitro study of changes in dental crown materials and in randomized clinical trial of changes in oral health status
Referente interno	Andrea Scribante, DDS PhD MHA MSc
Investigatore principale	Carolina Maiorani, RDH
Durata stimata intervento	24 mesi
Materiali utilizzati	Feldspatic ceramic, Zirconia, Lithium disilicate AIRFLOW® PLUS EMS Mini Piezon EMS; PI EMS
Intervento in vitro	no
Tipologia	-
Variabili	-
Intervento clinico	Presente
Tipologia	Studio osservazionale su due differenti metodiche di pulizia
Variabili	probing pocket depth bleeding on probing the plaque index
Randomizzazione partecipanti	Si mediante tabelle di randomizzazione
Dichiarazione di Helsinki	Rispettata
Consenso informato	Si
Presenza di procedure invasive	No
Presenza di interventi non codificati	No
Software Analisi Dati	R (v. 3.1.3, R Develop Core Team, R Foundat for Stat Comput, Wien, Austria)
Calcolo Numeroisità campionaria	Si (studio clinico)
Statistica descrittiva	Media, deviazione standard, minimo, mediana e massimo
Statistica inferenziale	Kolmogorov-Smirnov e analisi di varianza
Significatività	P<0.05
Giudizio	**Eseguibile**