

The impact of operator access on implant surface roughness following implantoplasty procedures. An *in vitro* study.

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D.Ch.Dent. (Periodontology)

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Academic Declaration

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Eamonn Donohoe

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Summary

This *in vitro* investigation sought to determine whether access to the implant during implantoplasty (IP) exerts a significant influence on the resulting surface roughness and material loss, by comparing outcomes obtained in a phantom head model versus a tabletop model. Secondary objectives were to compare the surface roughness and material loss resulting from IP among three commercially available dental implant systems, and to assess differences between the buccal and lingual aspects of implants in the phantom head model.

Implants from three different implant systems, Straumann®, Ankylos®, and Sweden & Martina®, were used. A total of 42 implants were utilised. 21 implants, seven of each implant type, were mounted in either the tabletop or phantom head model. The implants on the tabletop model were mounted in a vice, giving the operator unrestricted access to the surface during IP. Implants in phantom head models were mounted into casts in the 36 sites using a customised jig. A standardised bur sequence was employed for IP of all implants, and a single operator performed all IP procedures. Two tungsten carbide burs with different blade anatomy were used, followed by a final surface polishing sequence with silicone polishers. This sequence was applied consistently across all implant types and both models, with implant removal from the models after.

Surface profilometry was conducted using a Surftest Sj-210 contact stylus profilometer (Mitutoyo Europe GmbH, Neuss, Germany) in order to measure surface roughness in the form of Ra and Rz values. To provide qualitative data, images using a Carl Zeiss EVO LS10 (Zeiss, Oberkochen, Germany) were taken of select implant surfaces. In addition, implant mass and width were measured before and after the IP. The amount of time needed for each IP procedure was also measured using a Garmin® Venu® 2 Plus (Garmin International Inc., Olathe, USA).

Descriptive statistics (means with standard deviations, and medians with interquartile ranges) were calculated for all measured parameters. The Shapiro–Wilk test was used to assess normality. Inferential statistics compared outcomes between model settings and

among implant systems using parametric or non-parametric tests, with post-hoc adjustments for multiple comparisons. A significance threshold of $p < 0.05$ was applied.

After IP, implants in the phantom head setting achieved a median Ra value of $0.53\ \mu\text{m}$ ($0.49 - 0.58\ \mu\text{m}$) compared to those in the tabletop setting of $0.44\ \mu\text{m}$ ($0.37 - 0.62\ \mu\text{m}$) ($p = 0.004$). In addition, implants in the phantom model achieved a significantly increased Rz of $2.47\ \mu\text{m}$ ($1.98 - 2.75\ \mu\text{m}$) compared to $2.78\ \mu\text{m}$ ($2.56 - 3.01\ \mu\text{m}$) ($p = 0.019$). Procedural time was significantly less for implants prepared in standardised tabletop conditions (685 sec [648 – 738]) compared to those prepared in a simulated clinical environment in phantom heads (765 sec [733 – 800.50]) ($p < 0.001$).

Material loss varied among implant systems, with Straumann® implants exhibiting a greater reduction in mass and width than Ankylos® and Sweden & Martina® implants. No significant differences between implant types were found for Ra and Rz ($p > 0.05$). In addition, there were no significant differences in Ra and Rz between the buccal and lingual aspects of the implants in the phantom head setting overall and for the implant types.

The results demonstrate that IP can effectively reduce the surface roughness of dental implants, though the final surface roughness and procedural time are affected by operator access. In addition, no significant differences in final surface roughness were observed between the different implant types following IP. Associated material loss (mass and width reduction) appears to be influenced by implant macro-design, such as thread density and thread depth.

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List of Abbreviations

BoP	Bleeding on probing
FDP	Fixed dental prostheses
IP	Implantoplasty
ML	Mucosal level
NHANES	National Health and Nutrition Examination Surveys
PD	Probing depth
PI	Plaque index
PT	Polished titanium
Ra	2D arithmetic average surface roughness
RAL	Relative attachment level
RCT	Randomised controlled trial
Rz	Maximum height of surface (2D)
Sa	3D arithmetic average surface roughness
SLA	Sandblasted, large-grit, acid-etched
SoP	Suppuration on probing
Sz	Maximum height of surface (3D)
TBZ	Titanium and zirconia blasted
TBZA	Titanium and zirconia blasted and acid-etched
TGF- β_2	Transforming Growth Factor Beta 2
Ti-6Al-4V	Titanium alloy (90% Ti, 6% Al, 4% V)
WMD	Weighted mean difference

1. Literature review

1.1 Introduction

Dental implants are alloplastic medical devices that are surgically inserted into the maxilla or mandible to enable the loading of a suprastructure, facilitating the restoration of a patient's masticatory function, aesthetics, phonetics, and comfort (Resnik, 2020). There are various types of dental implants, including blade form, subperiosteal, ramus frame, and endosseous (root form) implants (Gaviria *et al.*, 2014). Endosseous implants are the most commonly used due to the higher failure rates associated with other implant design types (Albrektsson *et al.*, 1986).

Elani *et al.* (2018) analysed data from the National Health and Nutrition Examination Surveys (NHANES) from 1999 to 2016 and found an increasing prevalence of dental implants in US adults, from 0.7% in 1999-2000 to 5.7% in 2015-2016. The age groups experiencing the most significant increase were those aged 55 to 64 years and 65 to 74 years, respectively. Interestingly, the placement of dental implants in patients aged 65 years or older did not appear to have an increased rate of early implant failure compared to younger patients (Elani *et al.*, 2018).

In Ireland, there is a trend of increasing edentulism among older age groups of the population, with 18% of patients over 54 years experiencing complete edentulism (Sheehan *et al.*, 2017). Edentulism, along with difficulties in chewing and a reduced number of functional occluding tooth pairs, has been linked to a diminished quality of life (Tsakos *et al.*, 2006; Hugo *et al.*, 2009). However, the rehabilitation of patients with fixed or removable implant-supported prostheses has been shown to improve oral health-related quality of life (Duong *et al.*, 2022).

Overall, implants have demonstrated a high survival rate of 94.6%, with a follow-up period of 13.4 years (Moraschini *et al.*, 2015). However, implant survival simply refers to the physical presence of the implant within the oral cavity, without accounting for its functional or clinical condition (Resnik, 2020). Albrektsson *et al.* (1986) defined

parameters for implant success as no implant mobility, no pain or discomfort, no peri-implant infection, marginal bone loss of 'less than 1.5 mm of bone loss in the first year after placement, and then less than 0.2 mm of bone loss per year thereafter' and no pathological changes in the surrounding tissues. Papaspyridakos *et al.* (2012) demonstrated that as the number of parameters used to evaluate implant success increases, the reported success rates of dental implants tend to decrease.

Jung *et al.* (2012) reported the 5-year survival of implants supporting single crowns to be 97.2% (95% CI: 96.3-97.9%), while the implant-supported crown survival was 96.3% (95% CI: 94.2-97.6%). Soft tissue complications, including signs of inflammation, bleeding, suppuration, peri-implantitis, and dehiscence, occurred in 7.1% (95% CI: 4.4-11.3%) of implants, while 5.2% (95% CI: 3.1-8.6%) of implants experienced more than 2 mm of bone loss. Technical complications, such as screw loosening, loss of crown retention, and fracture of veneering material, were also common. Implant-supported fixed dental prostheses (FDPs) fabricated with metal-ceramic had a higher 5-year survival rate of 98.7% (95% CI: 96.8%-99.5%) compared to zirconia-ceramic implant prostheses 93.0% (95% CI: 90.6%-94.8%)($p < 0.001$) (Sailer *et al.*, 2018). Zirconia-ceramic FDPs had a significantly higher ($p < 0.001$) rate of chipping or fracture of 50% compared to 11.6% for metal-ceramic reconstructions. However, there were inadequate studies to conduct a meta-analysis of biological complications (Sailer *et al.*, 2018). In addition, removable implant-supported prostheses have been associated with the loss of retentive mechanisms, the need for relining, overdenture attachment fracture, and a correlation with the loss of maxillary implants (Goodacre *et al.*, 2003).

Peri-implantitis is a biofilm-associated pathological condition affecting dental implants, characterised by inflammation of the surrounding connective tissue and progressive bone loss (Berglundh *et al.*, 2018; Schwarz *et al.*, 2018). Peri-implantitis, peri-implant mucositis, and peri-implant health are considered a spectrum of peri-implant diagnoses, with changes occurring due to the presence of microbial biofilm (Herrera *et al.*, 2023). The clinical features of peri-implantitis include the presence of bleeding or suppuration on probing, probing depths (PD) of ≥ 6 mm, or an increase from previous examinations

(Berglundh *et al.*, 2018). Furthermore, bone loss must be present beyond the changes expected from initial remodelling, or bone levels $\geq 3\text{mm}$ apical to the most coronal part of the intraosseous part of the implant if previous examination data is unavailable (Berglundh *et al.*, 2018; Herrera *et al.*, 2023). The disease process is often asymptomatic as it progresses (Romandini *et al.*, 2021). Lee *et al.* (2017) found a mean peri-implantitis prevalence of 9.25% at implant-level, and 19.83% at subject-level.

The “Prevention and treatment of peri-implant diseases—The EFP S3 level clinical practice guideline” recommends an initial non-surgical step of therapy, including oral hygiene instructions, risk factor control, prosthesis maintenance, and modification as required, along with supra- and sub-marginal instrumentation (Herrera *et al.*, 2023). If the endpoints of non-surgical therapy are not achieved, surgical therapy involving access flaps, resective surgery, or regenerative surgery can be used (Donos *et al.*, 2023; Herrera *et al.*, 2023; Karlsson *et al.*, 2023).

Implantoplasty (IP) is a resective procedure that involves smoothing the implant surface, usually with rotary instruments, which can be used as an adjunct to the surgical management of peri-implantitis (Romeo *et al.*, 2005). IP aims to remove bacteria adherent to exposed implant surfaces along with the removal of implant threads, allowing improved biofilm control (Roccuzzo *et al.*, 2024). However, it has been shown that achieving an average surface roughness (Ra) of less than $0.2\text{ }\mu\text{m}$ has no significant impact on supra- or subgingival plaque composition (Bollen *et al.*, 1996; Quirynen *et al.*, 1996). Currently, IP for implant surface decontamination during the surgical management of peri-implantitis is not recommended due to limited evidence supporting its use (Herrera *et al.*, 2023; Ramanauskaite *et al.*, 2023).

This literature review aims to discuss concepts related to implant surface roughness, IP, and to examine studies that evaluate the average surface roughness (Ra/Sa) achieved by various bur protocols for IP in different settings.

1.2 Dental Implants

Dental implants can be composed of metal, ceramic and polymers (Sykaras *et al.*, 2000). The materials most commonly used in practice are titanium, titanium alloys (mainly Ti-6Al-4V), titanium-zirconia, or zirconia (Saini *et al.*, 2015). Titanium and titanium-zirconia have an oxidative layer, which enables biocompatibility, allowing the material to be accepted by the host (Sykaras *et al.*, 2000; Murphy *et al.*, 2017). Zirconia exists in an oxidised state as zirconium dioxide, which contributes to biocompatibility and osseointegration (Sollazzo *et al.*, 2008).

Primary stability refers to the mechanical interlocking between the implant and bone (Heimes *et al.*, 2023; Stoilov *et al.*, 2023). The magnitude of the primary stability is determined by many factors, including the macro-design of the implant (i.e. diameter, length, cylindrical vs tapered, thread architecture), the implant bed preparation (i.e. press-fit), the vertical position of the implant relative to the bone crest (i.e. sink depth), the surface morphology or roughness of the implant (i.e. micro- and nano topography), and the local bone quality (i.e. density of bone) (Bosshardt *et al.*, 2017). Tapered implants have been shown to produce higher and more evenly distributed vertical and lateral compressive forces compared to cylindrical implants (Li *et al.*, 2020). These compressive forces may contribute to increased primary stability (Heimes *et al.*, 2023). Primary implant stability has been identified as a key factor in the success of osseointegration (Albrektsson *et al.*, 1981).

Micromotion of a dental implant during the early phase of healing can lead to fibrous tissue encapsulation and implant failure (Szmukler-Moncler *et al.*, 1998). There is a threshold amount of micromotion that can be tolerated during osseointegration, ranging from 50 to 150 μm , although excessive amounts will lead to implant failure (Szmukler-Moncler *et al.*, 1998, 2000).

In contrast to primary stability, secondary implant stability refers to the long-term biological stability of an implant achieved through osseointegration, during which direct bone-to-implant healing occurs (Bosshardt *et al.*, 2017). Implant surface modifications

and surface treatments of dental implants aim to enhance the speed and predictability of osseointegration while increasing long-term success (Barfeie *et al.*, 2015). During this transitional healing period, the overall implant stability reduces approximately three weeks after implant placement as remodelling occurs, and there is a subsequent reduction in primary implant stability (Berglundh *et al.*, 2003; Bosshardt *et al.*, 2017). Secondary stability begins with the deposition of new bone onto the implant surface (Salvi *et al.*, 2015). As the process of osseointegration progresses, the primary stability of the implant decreases, and secondary stability becomes the primary source of support for the implant (Raghavendra *et al.*, 2005; Bosshardt *et al.*, 2017).

1.2.1 Osseointegration

Osseointegration has been defined as “a direct, structural and functional connection between ordered, living bone and the surface of a load-carrying implant” (Brånemark *et al.*, 1985). A clinical definition was developed, which described osseointegration as “A process whereby clinically asymptomatic rigid fixation of alloplastic materials is achieved and maintained in bone during functional loading” (Brånemark *et al.*, 1985).

Osseointegration involves a complex, orchestrated cascade of cellular healing processes (Terheyden *et al.*, 2012; Salvi *et al.*, 2015). The steps in peri-implant bone healing can be outlined as follows: haemostasis and formation of a coagulum, granulation tissue formation, bone formation, and bone remodelling (Bosshardt *et al.*, 2017).

During osseointegration, bone healing occurs through a process of distance and contact osteogenesis (Davies, 2003). Contact osteogenesis describes the formation of *de novo* directly onto the implant surface by osteoblasts (Davies, 2003). Contact osteogenesis is considered the first phase of osseointegration for dental implants (Bosshardt *et al.*, 2017). Distant osteogenesis refers to the formation of new bone emanating from the existing bone of the implant bed preparation, which then extends into the provisional connective tissue (Davies, 2003).

1.2.2 Osseointegration and implant surface roughness

Dental implants initially were developed with a moderately smooth, turned implant surface (Brånemark *et al.*, 1985). There was then a transition from the use of turned machined implants to those with a roughened implant surface (Cooper *et al.*, 1999). This increased roughness allows for a larger surface area available, enhanced cell attachment, increased bone contact on the implant surface, and improved biomechanical interaction between the implant and bone (Cooper *et al.*, 1999). These factors enable more predictable osseointegration, promote bony healing, and facilitate earlier prosthetic loading times (Guéhenneuc *et al.*, 2007). The surface roughness of dental implants plays a pivotal role in the healing cascade and in achieving osseointegration (Albrektsson and Wennerberg, 2019).

1.2.2.1 Implant surface roughness classification

The surface roughness of dental implants is categorised based on their arithmetic average surface roughness (Sa). Surfaces with Sa values between 0.0–0.4 µm are considered smooth, 0.5–1.0 µm minimally rough, 1.0 – 2.0 µm moderately rough, and above 2.0 µm as rough (Wennerberg and Albrektsson, 2010).

1.2.2.2 Clinical performance

A Cochrane review and meta-analysis conducted by Esposito *et al.* (2014) found that early implant failure in roughened dental implants was 50 per 1000, while implants with turned surfaces had 140 failures per 1000 implants placed. This resulted in relative risk of early implant failure for turned implants of 2.79 (95% CI, 0.87–8.90), although this did not reach statistical significance ($p = 0.08$) (Esposito *et al.*, 2014). This indicates that implants with turned surfaces tend to fail earlier than those with roughened surfaces (Esposito *et al.*, 2014). Interestingly, turned implants had a lower relative risk of being affected by peri-implantitis compared to implants with roughened surfaces (0.80; 95% CI, 0.67–0.96; $p = 0.01$) (Esposito *et al.*, 2014). However, other studies have shown that implant surface modification does not influence the presence of peri-implantitis (Renvert *et al.*, 2011; Stavropoulos *et al.*, 2021).

1.2.2.3 Histological comparison

Abrahamsson *et al.* (2004) used a canine model to investigate the rate and degree of osseointegration of sandblasted, large-grit, acid-etched (SLA) implants compared to turned implants. The Sa of the SLA surface was $2.29 \pm 0.59 \mu\text{m}$, and the turned (smooth) control implants were $0.35 \pm 0.17 \mu\text{m}$. The bone-to-implant contact percentage of the intra-osseous portion of the SLA implants was significantly ($p < 0.05$) increased at one, two, four, six, eight-, and twelve-weeks post-implant insertion when compared to the turned implants. In addition, the authors found that SLA implants had more initial woven bone formation and earlier lamellar bone formation at the bone interface. The authors concluded that the rate and degree of osseointegration were superior for SLA implants compared with those with turned surfaces (Abrahamsson *et al.*, 2004).

Wennerberg and Albrektsson (2009) proposed that moderate surface roughness (Sa 1 - 2 μm) creates an optimal environment for connective tissue and bone cells, leading to the highest bone-to-implant contact achieved of all implant roughness types. They hypothesised that on smooth surfaces, friction is too small for cellular retention, while on very rough surfaces, due to the diminished distance between peaks, the cells may perceive the surface as smooth (Wennerberg and Albrektsson, 2009).

1.2.2.4 Cellular responses

Mustafa *et al.* (2001) used cultures of osteoblast-like cells from human mandibular bone and found they exhibited the most significant amount of proliferation and differentiation *in vitro* on moderately rough surfaces (Sa = 1.38 μm) compared to turned implant surfaces (Sa = 0.2 μm). However, cellular attachment assessed after three hours was not significantly different (Mustafa *et al.*, 2001). In addition, Marinucci *et al.* (2006) found that human osteoblasts on macro-sandblasted (Sa = 3 μm) and micro-sandblasted (Sa = 0.5 μm) titanium surfaces exhibited increased proliferation, secretion of TGF- β_2 , and expression of osteopontin, Runx2, and bone sialoprotein compared to machined controls *in vitro*.

In contrast, for fibroblasts, smooth titanium surfaces support the attachment and proliferation of these cells more effectively than roughened surfaces (Könönen *et al.*, 1992; Mustafa *et al.*, 1998).

1.2.2.5 *Methods of surface modifications*

Implant dental surfaces can be modified using mechanical methods (e.g., grinding, blasting, machining, and polishing), chemical processes (e.g., acid treatments, anodisation), or physical means (e.g., plasma spraying or sputtering) (Barfeie *et al.*, 2015).

For example, Straumann® implants with an SLA surface treatment are large-grit blasted with aluminium oxide particles and acid-etched using a mixture of hydrochloric and sulfuric acid (Wennerberg and Albrektsson, 2010). The average surface roughness achieved is a Sa of 1.78 µm (Wennerberg and Albrektsson, 2010). This surface roughness is comparable to that of Ankylos® implants, which are also subjected to large grit blasting with aluminium oxide particles and high-temperature acid etching, achieving a Sa of 1.62 µm (Dohan Ehrenfest *et al.*, 2011). Similarly, Sweden & Martina® uses zirconia oxide sandblasting and performs subsequent acid etching of their implant surfaces, achieving a median Sa of 1.6 µm (Giffi *et al.*, 2022).

1.3 Measurement of surface roughness

The surface roughness of a material is evaluated by measuring the peaks and valleys present relative to a reference plane (Dohan Ehrenfest *et al.*, 2010; Dagnall, 2011). In addition to surface roughness, material texture can be described through its waviness and form (Dagnall, 2011). Surface roughness can be assessed using two-dimensional or three-dimensional measurement tools, which are then represented by their corresponding quantitative parameters (Dagnall, 2011). The direct comparison of two-dimensional and three-dimensional profilometry measurements is not possible, although some correlation between the measurements is present (Dagnall, 2011).

1.3.1 Contact profilometry

Contact profilometers utilise a mechanical stylus tip that moves across the material surface, which is attached to a cantilever (Wennerberg and Albrektsson, 2000). As the stylus arm traverses the surface, vertical movements are recorded, producing the final measurement of surface roughness (Wennerberg and Albrektsson, 2000). In addition to two-dimensional roughness measurement, a stylus contact profilometer can be used to acquire three-dimensional measurements. This technique can provide a high degree of spatial resolution, although it is slow and may be prone to inaccuracy due to vibration (Dagnall, 2011).

The use of a contact stylus profilometer can lead to wear and contamination of the stylus tip and wear of the test material surface if the stylus has a harder tip, which may lead to inaccurate measurement and lower resolution compared to three-dimensional measurement tools (Wennerberg and Albrektsson, 2000; Ruzova and Haddadi, 2025). Moreover, contact profilometers cannot evaluate threaded implant designs, and surface roughness may differ significantly at different locations of a particular implant (Wennerberg and Albrektsson, 2000). However, contact profilometry has a higher level of accuracy when compared to non-contact profilometry (Dagnall, 2011).

1.3.2 Non-contact profilometry

Non-contact profilometry uses optical methods to analyse surface topography without physically touching the surface (Ruzova and Haddadi, 2025). This technique can be through the use of laser triangulation, confocal microscopy and scanning interferometry (Wennerberg and Albrektsson, 2000; Dagnall, 2011).

These techniques eliminate the risk of surface damage to the material being measured, along with increased measurement speed (Dagnall, 2011). In addition, there is an increased resolution compared to stylus profilometry (Wennerberg and Albrektsson, 2000; Dagnall, 2011)

However, accuracy may be lower than that of contact profilometry as the material's reflectivity and sharp points may affect the reflected light and act as secondary sources of light (Wennerberg and Albrektsson, 2000; Dagnall, 2011). The slope of the surface may impact the scatter of the light, leading to less accurate results (Wennerberg and Albrektsson, 2000). Furthermore, polished surfaces can give an overestimation of surface roughness when assessed with non-contact profilometry instruments (Wennerberg and Albrektsson, 2000). In addition, non-contact profilometry will not be able to "sweep" debris from the surface, unlike a stylus tip, leading to inaccurate surface readings (Dagnall, 2011).

However, the use of scanning electron microscopy, rather than providing a quantitative measure, allows for the visualisation of qualitative morphological aspects of the surface being examined (Wennerberg and Albrektsson, 2000). This type of surface analysis can be prone to subjectivity, although it allows for morphology characterisation of the surface (Wennerberg and Albrektsson, 2000; Dohan Ehrenfest *et al.*, 2010)

1.3.3 Surface roughness measurement parameters

Surface roughness measures are based on the characteristics of the material being quantified, including the amplitude of peaks and valleys, spacing of irregularities, and hybrid parameters determined by the combination of amplitude and spacing (Dagnall,

2011). ISO 21920 outlines the standards for the two-dimensional measurement of surface texture (roughness) of various materials, including dental implants, and recommends reporting the values of Ra (arithmetic mean height) and Rz (maximum height of surface), although, additional parameters can be assessed when reporting on implant surface roughness (International Organization for Standardization, 2021). Two-dimensional measurements are denoted with an “R” letter (e.g. Ra), while three-dimensional surface analysis is denoted with an “S” (e.g. Sa) (Dohan Ehrenfest *et al.*, 2010). However, these measurements are not comparable (Dagnall, 2011).

The average roughness (Ra) of the surface is the most commonly reported surface characteristic, representing the mean of the height values of the peaks and valleys on the evaluated surface (Dagnall, 2011). Ra represents average roughness by averaging out atypical peaks or valleys without distinguishing their shapes or differentiating between peaks and valleys (Dagnall, 2011).

The “Ten-point Height of Irregularities” (Rz) is the average height between the five highest peaks and the five deepest valleys (Dagnall, 2011). This measurement allows for the visualisation of the extreme irregularities of the surface profile (Dagnall, 2011).

1.4 Peri-implantitis

Peri-implantitis is a biofilm-associated condition that affects dental implants and is characterised by soft tissue inflammation as well as progressive bone loss (Schwarz *et al.*, 2018). The bone loss associated with peri-implantitis progresses in a nonlinear and acceleratory pattern (Derks *et al.*, 2016).

Peri-implantitis is preceded by peri-implant mucositis, which, if treated successfully with submarginal instrumentation, can restore peri-implant tissue health (Herrera *et al.*, 2023). However, if the disease progresses to peri-implantitis, then peri-implant health cannot be achieved (Herrera *et al.*, 2023). Peri-implantitis is regarded as an irreversible condition, indicating that even after peri-implant stability is achieved, the implant is classified as having 'stable' peri-implantitis (Herrera *et al.*, 2023)

Lee *et al.* (2017) found a mean peri-implantitis prevalence of 9.25% (95% CI; 7.57, 10.93) at implant-level, and 19.83% (95% CI; 15.38, 24.27) at subject-level. Meta-analysis was performed on data from 47 studies. However, the reported prevalence figures may not align with the current case definition of peri-implantitis, as the use of differing case definitions has been associated with different prevalence rates reported (Shimchuk *et al.*, 2021).

A diagnosis of peri-implantitis, when prior clinical records are available, requires: 1) the presence of bleeding and/or suppuration on gentle probing, 2) an increase in PD from baseline measurement, and 3) the presence of bone loss beyond changes in crestal bone level from initial bone remodelling (Berglundh *et al.*, 2018; Schwarz *et al.*, 2018). When previous records are not available, peri-implantitis diagnosis is based on 1) the presence of bleeding and/or suppuration upon gentle probing, 2) PDs $\geq 6\text{mm}$, and 3) bone levels $\geq 3\text{mm}$ apical to the most coronal portion of the intra-osseous part of the implant (Berglundh *et al.*, 2018; Schwarz *et al.*, 2018).

Carcuac *et al.* (2013) used a canine model and demonstrated that ligature-induced peri-implantitis resulted in a more extensive inflammatory lesion than that observed in

periodontitis. Notably, this lesion extended closer to the alveolar bone crest and was characterised by a greater presence of neutrophils and osteoclasts, suggesting a more aggressive tissue breakdown associated with peri-implantitis. These observations align with findings from human biopsy studies. Carcuac and Berglundh (2014) reported that peri-implantitis lesions in humans were larger and also exhibited a higher density of inflammatory cells, including plasma cells, macrophages, and neutrophils. Additionally, the inflammatory infiltrate in peri-implant tissues extended apically beyond the pocket epithelium and lacked the encapsulation of organised connective tissue fibres typically found in periodontitis lesions (Carcuac and Berglundh, 2014). These findings show a distinct difference in the host response between peri-implantitis and periodontitis.

Mombelli *et al.* (1987) conducted microbial cultures on five patients with successful dental implants and seven patients with failing implants, characterised by a PD of 6mm or more, suppuration, and visible loss of alveolar bone. Diseased areas exhibited diverse microbial populations dominated by gram-negative anaerobic rods, with black-pigmented *Prevotella* and *Fusobacterium* species frequently observed (Mombelli *et al.*, 1987). Furthermore, spiral-shaped bacteria, fusiform microbes, and motile, curved rods were consistently seen under darkfield microscopy at infected sites (Mombelli *et al.*, 1987). In contrast, healthy control sites within the same individuals contained minimal bacterial populations, primarily composed of coccoid organisms, while spirochetes were absent, and fusiform, motile, and curved rods appeared only rarely and in minimal quantities (Mombelli *et al.*, 1987). Interestingly, the microbiome at control sites in both unsuccessful and successful cases exhibited a similar microbial composition (Mombelli *et al.*, 1987). Building upon these findings, Leonhardt *et al.* (1999) performed DNA-DNA hybridisation on microbial analysis of 37 patients that had one or more implants with bone loss of ≥ 3 threads, bleeding, and/or suppuration on probing, and 51 patients with peri-implant health. Their results demonstrated that peri-implantitis sites were positive for *A. actinomycetemcomitans*, *P. intermedia*, and *P. gingivalis* in 60% of cases and that microbes not typically associated with periodontitis were isolated in 55% of cases (e.g. *Staphylococcus* spp., enterics and *Candida* spp.). In contrast, implants surrounded by healthy peri-implant tissues had a similar microbiota to that present in periodontal

health (Leonhardt *et al.*, 1999).

de Waal *et al.* (2017) performed a case-control study using 85 peri-implantitis cases and found the presence of *P. gingivalis*, *P. intermedia*, *T. forsythia*, and *F. nucleatum* were strong risk indicators for peri-implantitis (de Waal *et al.*, 2017). Moreover, a meta-analysis conducted by Carvalho *et al.* (2023) found significant associations between peri-implantitis and the presence of microbial species, including *S. epidermidis*, *F. nucleatum*, *T. denticola*, *T. forsythia*, *P. intermedia*, and *P. gingivalis*, all of which were more prevalent in peri-implantitis compared to non-affected controls (Carvalho *et al.*, 2023). The microbiome associated with peri-implantitis has been found to exhibit reduced diversity compared to periodontitis and periodontal health (Kim *et al.*, 2023). However, despite the reduced spectrum of microbial diversity and associations, the presence of specific microbes is merely a risk indicator. There are no specific bacteria or proinflammatory cytokines identified in the pathogenesis of peri-implantitis (Berglundh *et al.*, 2018).

1.4.1 Risk factors and risk indicators for peri-implantitis

Risk factors are causally related to disease and are established through the use of longitudinal studies (Heitz-Mayfield, 2008; Schwarz *et al.*, 2018). In contrast, risk indicators are variables associated with the disease but not confirmed to be causally related, typically identified through the use of observational, cross-sectional or retrospective studies (Heitz-Mayfield, 2008; Schwarz *et al.*, 2018). The identification and modification of risk factors and indicators of peri-implantitis are critical steps in the prevention and treatment of peri-implantitis (Herrera *et al.*, 2023).

The 2017 World Workshop on peri-implantitis noted that poor plaque control, a lack of regular maintenance, and a history of periodontitis provided the most substantial evidence as risk factors for peri-implantitis, whereas smoking and diabetes had inconclusive evidence (Schwarz *et al.*, 2018). More recently, a systematic review and meta-analysis found several risk factors for the diagnosis of peri-implantitis, including uncontrolled diabetes and irregular attenders at supportive periodontal programmes

(Carra *et al.*, 2023). The meta-analysis performed showed that patients with good glycaemic control had a reduced risk of a diagnosis of peri-implantitis (OR 0.16, 95% CI [0.03, 0.96], $p = 0.04$) compared to patients with poor glycaemic control (HbA1c > 8%) (Carra *et al.*, 2023). In addition, patients participating regularly in a supportive periodontal and peri-implant supportive care protocol had a significantly reduced risk of peri-implantitis (OR 0.45, 95% CI [0.30, 0.68]) compared to those who attended irregularly. In addition, patients attending irregularly had a significantly increased risk of implant loss at implant level analysis (OR 3.76, 95% CI; 1.50 – 9.45, $p = 0.005$). The authors found that implant sites with augmented peri-implant keratinised mucosa had reduced bleeding on probing (BoP) (OR -1.18, 95% CI; -1.85 – -0.51, $p = 0.0006$) and lower marginal bone level changes (OR -0.25, 95% CI; -0.45 – -0.05, $p = 0.01$). However, the authors were unable to determine whether this measure could reduce the risk of peri-implantitis (Carra *et al.*, 2023).

Risk indicators of peri-implantitis include the lack of peri-implant keratinised mucosa (<2mm), the use of cement-retained implant crowns or the presence of excess cement, over-contoured and uncleanable implant prosthesis, implant malposition and occlusal overload (Esposito *et al.*, 2014; Schwarz *et al.*, 2018). In addition, factors such as biocorrosion, the presence of titanium particles within peri-implant tissues, and surface roughness of the implant surface may have an impact on the onset and progression of peri-implantitis (Esposito *et al.*, 2014; Schwarz *et al.*, 2018).

A systematic review and meta-analysis by Esposito *et al.* (2014) showed that integrated implants with turned surfaces after three years in function were less likely to be affected by peri-implantitis (RR 0.80; 95% CI: 0.67 – 0.96; $p = 0.014$) when compared to implants with roughened surfaces. However, the results of the meta-analysis are heavily influenced by a single study, Engquist *et al.* (2002), which contributed to 98.6% of the overall weighting of the meta-analysis. This weighting is disproportionate, and so the results should be interpreted with caution. However, a systematic review by Stavropoulos *et al.* (2021) found the risk of peri-implantitis associated with implants that have modified surfaces is comparable to those with turned implant surfaces when the

follow-up period is five years or more. The authors included 20 randomised controlled trial (RCT) (1183 patients with 2852 implants), three prospective non-randomised controlled trials (152 patients with 223 implants), four prospective cohort studies (640 patients with 1948 implants), and four retrospective studies (5630 patients with 21,133 implants) as part of their descriptive analysis. However, only a descriptive analysis was used, and a meta-analysis was not performed due to the heterogeneity of the studies.

In addition to implant surface treatments, it has been hypothesised that peri-implant inflammation can be attributable to the presence of titanium particles in the peri-implant tissues, which may propagate peri-implant inflammation, leading to peri-implantitis (Schwarz *et al.*, 2018). Titanium particles may be released into the peri-implant tissues after implant insertion, through wear at the implant-abutment connection, or through implantoplasty and corrosion processes (Mombelli *et al.*, 2018). Moderately rough dental implants are associated with an increased titanium particle release immediately after implant placement when compared to implants with turned surfaces (Pettersson *et al.*, 2017). Titanium particles have been found around implants in health and with peri-implantitis (Olmedo *et al.*, 2013). However, significantly higher concentrations of titanium particles have been found in the peri-implant soft tissues and peri-implant plaque samples associated with peri-implantitis (Olmedo *et al.*, 2013; Safioti *et al.*, 2017). However, currently, the evidence does not allow for a causative relationship to be established (Mombelli *et al.*, 2018).

1.5 Classification of peri-implantitis defects

Peri-implant defect morphology was first classified by Schwarz *et al.* (2007) when comparing ligature-induced and naturally occurring peri-implant defects in humans and dogs. Schwarz *et al.* (2007) classified these defects as intra-osseous (Class I) and supra-crestal bone loss (Class II). Class I defects were subclassified into a, b, c, d and e (Figure 1). The authors found that the most frequently identified defect in humans was Class Ie at 55.3%, followed by Ib (15.8%), Ic (13.3%), Id (10.2%) and Ia (5.4%). Class I defects were predominantly present with a class II supracrestal component. In this classification, they did not combine Class I and Class II defects (Schwarz *et al.*, 2007).

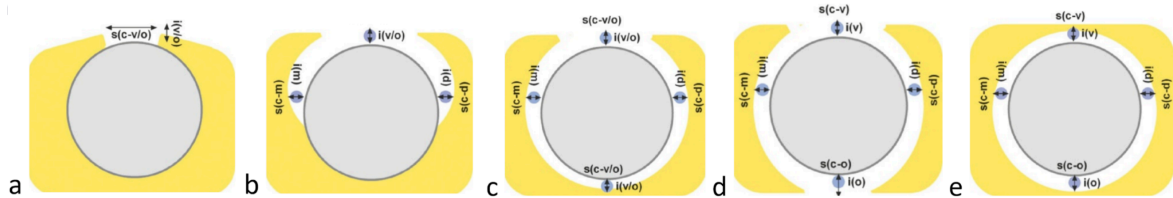


Figure 1: Classification of class I peri-implantitis defects as described by Schwarz *et al.* (2007).

Subsequently, Monje *et al.* (2019) proposed a classification for peri-implant defects which allowed for combined defects, both with infrabony and supra-crestal components. Class I defects are infraosseous defects, which are subclassified as follows: buccal dehiscence (Class Ia), 2-3 wall defect (Class Ib), and circumferential defect (Class Ic). Supracrestal defects are classified as Class II. Class III defects are combined defects of infraosseous and supracrestal components (Figure 2) (Monje *et al.*, 2019). In addition to defect morphology, the grade of defect depth was also considered in this classification: slight (S) with 3-4mm or < 25% of implant length, moderate (M) with 4-5mm or ≥25-50% of implant length and advanced (A) >6mm or >50% of implant length (Monje *et al.*, 2019).

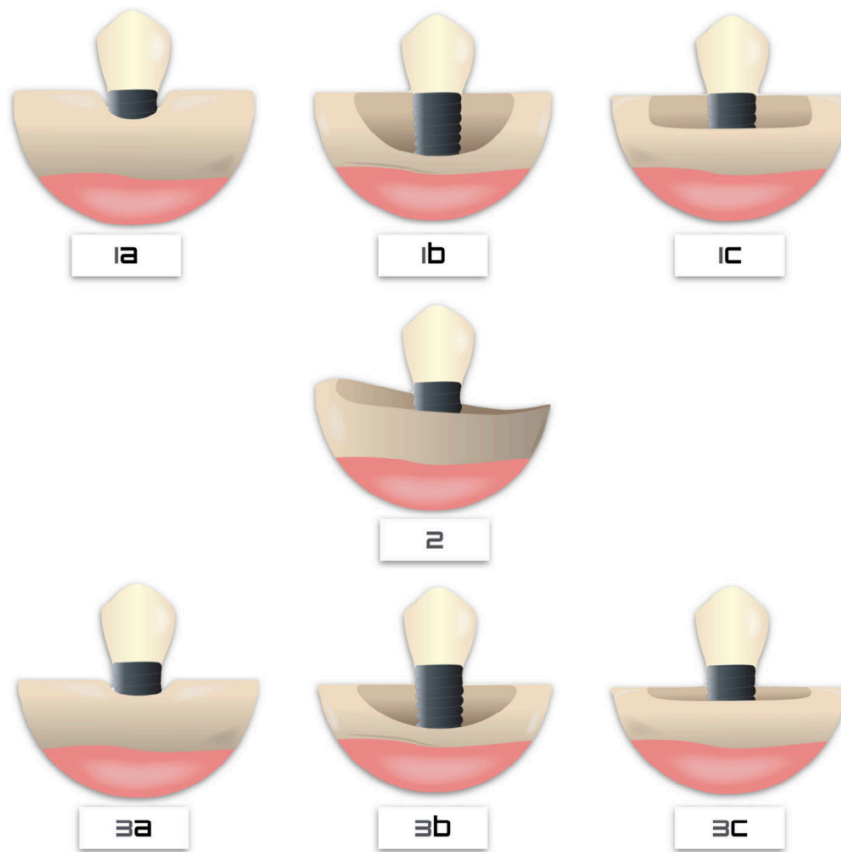


Figure 2: Classification of peri-implantitis defects as described by Monje et al. (2019).

Similar to Schwarz *et al.* (2007), the most frequently detected defect type at an implant level was class Ib (55%), followed by Ia (16.5%) and IIb (13.9%) (Monje *et al.*, 2019). Class II defects were the least frequently detected at 1.9% (Monje *et al.*, 2019). Implants were most commonly affected with moderate grade severity at 50.6% of implants (Monje *et al.*, 2019).

1.6 Management of peri-implantitis

Therapy of peri-implantitis aims to halt the inflammatory process and manage both systemic and local risk factors that may perpetuate the disease (Herrera *et al.*, 2023). It is currently recommended that peri-implantitis be initially managed through the reduction of existing modifiable risk factors and the use of an initial phase of non-surgical supra- and sub-gingival instrumentation (Herrera *et al.*, 2023). If the treatment endpoints are not reached, then a surgical phase utilising access flaps, resective surgery, reconstructive surgery or combined surgical therapy is recommended (Herrera *et al.*, 2023). When treatment endpoints are reached, it is recommended for patients to enter a supportive peri-implant care programme (Herrera *et al.*, 2023).

If the implant appears untreatable, exhibiting mobility, significant bone loss, or if peri-implantitis remains unresponsive to the previously mentioned treatments, removal of the implant may be required (Polyzois, 2019; Herrera *et al.*, 2023).

1.6.1 Non-surgical therapy

The primary objective of non-surgical therapy for peri-implantitis is to reduce peri-implant microbial biofilm and inflammation (Herrera *et al.*, 2023). Currently, it is recommended that oral hygiene instructions be given to patients along with risk factor control and prosthetic modification if required (Herrera *et al.*, 2023). Supra-gingival and submarginal instrumentation should be performed with curettes and/or ultrasonic devices (Cosgarea *et al.*, 2023; Herrera *et al.*, 2023). The use of air-polishing devices, diode lasers, desiccant antiseptic gels or antimicrobial photodynamic therapy as adjuncts or monotherapies for the non-surgical management of peri-implantitis are not currently recommended (de Waal *et al.*, 2022; Cosgarea *et al.*, 2023). In addition, the adjunctive use of locally administered antimicrobials in the non-surgical management of peri-implantitis is not suggested (Herrera *et al.*, 2023; Liñares *et al.*, 2023). The routine use of systemic antibiotics as an adjunct to non-surgical therapy is currently not recommended (Herrera *et al.*, 2023). However, clinicians may consider the use of antibiotics in select cases that have deep pockets $\geq 7\text{mm}$, extensive suppuration or with multiple and/or strategically affected implants, which could be retained over time (Herrera *et al.*, 2023). However, the use of systemic antibiotics during the non-surgical

phase of peri-implantitis management may still result in the patient progressing to surgical treatment in the long term (Hakkers *et al.*, 2024).

Re-evaluation should be completed after a period of six to twelve weeks while monitoring residual inflammation, suppuration, and PDs, along with good oral hygiene (Herrera *et al.*, 2023). Non-surgical instrumentation of peri-implantitis results in a reduction of probing depth of $\leq 1\text{mm}$ and a decrease in BoP of 20-50% (Renvert *et al.*, 2019). Blanco *et al.* (2022) performed a randomised placebo-controlled clinical trial on 32 patients evaluating the effect of the adjunctive use of systemic metronidazole with non-surgical therapy. Treatment success was allocated if “PD was reduced to 5 mm with no BoP or to $<5\text{ mm}$ irrespective of BoP, and no further bone loss was detected between baseline and 1 year” (Blanco *et al.*, 2022). After 12 months, 56.3% of patients in the antibiotics group and 25% of patients in the control group achieved treatment success (Blanco *et al.*, 2022). This finding shows that disease resolution, even with the use of antibiotics, is not predictable (Blanco *et al.*, 2022). In addition, it has been noted that complete disease resolution of advanced cases is unlikely (Renvert *et al.*, 2019).

The endpoints of non-surgical therapy, assessed at the implant level, are residual probing depths of $\leq 5\text{ mm}$ with no BoP at more than one point and no suppuration (Herrera *et al.*, 2023).

1.6.2 Methods of Management of Surgical Peri-implantitis

The surgical management of peri-implantitis can involve access flap or resective therapy, reconstructive approaches, or a combined surgical technique approach (Khoury *et al.*, 2019; Herrera *et al.*, 2023). All techniques involve the removal of inflammatory tissue and mechanical debridement of the implant surface, along with the raising of a mucoperiosteal flap (Herrera *et al.*, 2023). Patients entering surgical therapy for peri-implantitis should maintain adequate levels of oral hygiene (Herrera *et al.*, 2023).

Currently, systemic antibiotics are not recommended for use as an adjunct to surgical therapy (Herrera *et al.*, 2023). The use of systemic antibiotics and the surgical

management of peri-implantitis has recently been investigated by a systematic review by Teughels *et al.* (2023), which identified two randomised controlled trials. Hallström *et al.* (2017) performed a randomised controlled trial of open flap with or without systemic azithromycin in 39 patients. The mean difference in both groups for PD reduction was 1.7 mm (SD $\pm$ 1.1, 95% CI: 1.1, 2.3, $p < .001$) for the test group and 1.6 mm (SD $\pm$ 1.5, 95% CI: 0.8, 2.4, $p < .001$) for the control group. No significant differences were found for BoP, PDs, radiographic bone level and microbial load between the test and control groups after 1 year. However, when treatment success composite outcomes were evaluated (PD $\leq$ 5 mm, no BoP, no suppuration and no bone loss $\geq$ 0.5 mm) at 12 months, the test group had a 46.7% success rate, while 25.0% was found in the control group at 1 year. Similarly, Carcuac *et al.* (2017) performed a randomised controlled trial of 100 patients and 179 implants using a resective surgical approach with or without systemic amoxicillin. The authors found with an intention to treat analysis for treatment success (no bone loss $>$ 0.5mm, PD $\leq$ 5mm and no BoP or SoP) at implant level, that the antibiotic group had a 68.4% success rate at 3 years postoperatively, while the control group's success rate was 43.5%.

Recently, Riben Grundström *et al.* (2024) performed a blinded, single-centre, three-arm randomised placebo-controlled clinical trial with a 12-month follow-up on 84 patients (113 implants). Resective surgical approaches with bony recontouring were completed with or without systemic antibiotics; Group A received amoxicillin 500mg and metronidazole 400mg TDS for seven days, Group B received metronidazole 400mg TDS and phenoxymethylpenicillin 800mg BD for seven days, and Group C received a placebo. When treatment success (PD $\leq$ 5 mm, BoP $\leq$ 1 site, absence of SOP, absence of additional bone loss $>$ 0.5 mm) was assessed at one year, Group A (77%) had a significantly higher treatment success than Group C (33%) ($p = 0.004$). Similarly, Group B (69%) had a significantly higher success of treatment after one year when compared to Group C (33%) ($p = 0.023$) (Riben Grundström *et al.*, 2024).

It appears that there may be a short-term benefit ($<$ 1 year) in using antibiotics in the surgical management of peri-implantitis, although longer-term follow-up shows that this

reduces with time (Carcuac *et al.*, 2017; Hallström *et al.*, 2017; Riben Grundström *et al.*, 2024).

The endpoints of surgical therapy for peri-implantitis should be assessed at the implant level and include PDs ≤ 5 mm, ≤ 1 point of BoP, absence of suppuration on probing, and absence of progressive bone loss (Herrera *et al.*, 2023).

1.6.2.1 Access flaps and resective surgery

Access flap surgery provides direct access for implant surface decontamination while preserving the peri-implant hard and soft tissues through the use of a mucoperiosteal flap (Schwarz *et al.*, 2022). However, resective therapy aims to eliminate peri-implant pockets through the apical repositioning of a mucoperiosteal flap and/or bony recontouring (Schwarz *et al.*, 2022).

Karlsson *et al.* (2023) performed a systematic review and meta-analysis on randomised controlled trials to determine the long-term outcomes of access flap or pocket elimination therapy. Meta-analysis showed PD reduction was 2.2 mm (95% CI 1.8–2.7), a reduction of BoP after surgical therapy of 27% (95% CI 19.8–34.2) and a gain of 0.2mm MBL (95% CI –0.0 to 0.5). Meta-regression analysis revealed that the reduction in mean PD increased by 0.7mm (95% CI 0.5–0.9) for every millimetre increase in mean PD at baseline. The use of systemic antibiotics led to a significantly increased PD reduction 2.7 mm (95% CI 1.9–3.5) compared to treatment groups that had not taken antibiotics 1.7 mm (95% CI 1.5–2.0) ($p = .03$). However, the use of composite outcomes for treatment success (no bone loss >0.5 mm, PD ≤ 5 mm and no BoP) showed low treatment success rates of 17.6–33%. After 5 years, disease recurrence or progression occurs in 32.1 to 43.8% (Karlsson *et al.*, 2023). In addition, the weighted mean estimate of peri-implant mucosal recession of resective and access surgical techniques was 1.13mm (95% CI; 0.673 – 2) (Sanz-Martín *et al.*, 2021).

1.6.2.2 Implantoplasty

Implantoplasty is an adjunct to the surgical therapy of peri-implantitis, which aims to smooth and decontaminate the implant surface (Schwarz *et al.*, 2022). It may be viewed

as a form of resective therapy (Schwarz *et al.*, 2022). Implantoplasty is used to decontaminate the implant surface of biofilm and calcified deposits, while reducing bacterial adhesion, which may improve the efficacy of self-performed oral hygiene measures (Beheshti Maal and Verket, 2022).

IP can be performed by using a combination of different burs, which should allow for efficient cutting while providing a smooth, debris-free surface with a minimal scatter of titanium. Tungsten carbide burs have been shown to have better cutting efficiency than diamond burs (de Souza Júnior *et al.*, 2016; Beheshti Maal *et al.*, 2020; Yildiz *et al.*, 2022). For polishing, silicon polishing burs result in a smoother finish than Arkansas stone and a higher gloss value (Sahrmann *et al.*, 2019; Beheshti Maal *et al.*, 2020). However, silicon polishers have been associated with more pronounced debris after polishing, which may lead to contamination of the operating site (Ramel *et al.*, 2015; Tawse-Smith *et al.*, 2016).

However, current treatment guidelines state there is insufficient evidence to make any recommendation on the use of implantoplasty for the surgical management of peri-implantitis (Herrera *et al.*, 2023). This recommendation is based on a systematic review and meta-analysis performed by Ramanauskaite *et al.* (2023).

1.6.2.2.1 Advantages of IP

Romeo *et al.* (2005) conducted a randomised controlled clinical trial using resective surgery and implantoplasty in the test group, consisting of 10 patients (19 implants), and resective surgery only in the control group, with seven patients (16 implants). All implants were diagnosed with peri-implantitis (SoP or BoP, PD > 4mm, absence of implant mobility and evidence of radiographic bone loss). Follow-up after 24 months of treatment showed that PD, PAL, and modified bleeding index were significantly higher in the control group than in the test group. In addition, over this timeframe, two implants had been lost in the control group, whereas no implants were lost in the test group. Romeo *et al.* (2007) published radiographic findings which showed that implants treated with resective surgery and implantoplasty had a mean change of bone levels of

0–0.01 mm over three years, while the control group treated with resective surgery only had significantly increased bone loss of 1.44–1.54 mm, which was significant ($p < 0.05$) (Romeo *et al.*, 2007).

Bianchini *et al.* (2019) performed a study of 23 patients (32 treated implants) that had undergone combined resective surgery with implantoplasty and followed up for a period of two to six years (mean time: 3.4 ± 1.5 years). A total of four (13%) implants were lost or removed due to progressive bone loss or failure of osseointegration, while disease resolution was 83% at the patient level and 87% at the implant level at the follow-up time. In addition, there was a significant reduction in bleeding and suppuration on probing compared to baseline measurements. Bianchini *et al.* (2024) performed a follow-up of these treated implants. Four patients were followed up over a 6 to 11-year period (mean time: 7.75 ± 2.36 years). All four patients remained compliant with supportive therapy throughout the follow-up period. The authors observed a mean radiographic bone gain of 3.1 ± 1.84 mm from baseline at follow-up, with BoP and PD reducing by 67% and 2.5 mm, respectively, from baseline to follow-up (Bianchini *et al.*, 2024). However, this study included only four patients with a total of four implants (Bianchini *et al.*, 2024).

Monje *et al.* (2022) performed a retrospective study on 43 patients with 135 implants with a follow-up of 23.4 ± 8.9 months. Peri-implant defects were classified in their morphology and severity (Monje *et al.*, 2019). Resective surgery with implantoplasty was performed on class IA, II or IIIA defects, while reconstructive surgery with implantoplasty was performed on class IB, IIIB or IIIC defects (Monje *et al.*, 2019). Implant survival was 98% overall, while the resective surgery group had a significantly higher implant survival rate of 100% than the reconstructive surgery group of 90% ($p = 0.01$). Treatment success was defined as the absence of BoP and/or SoP, a probing depth of ≤ 5 mm, and no progressive radiographic bone loss of ≥ 1 mm. Overall, patient-level success was 35%, with no significant difference found between treatment modalities ($p = 0.14$). Overall, implant-level success was 66%, with the reconstructive approach achieving 61% success, although the difference between treatment groups was not significantly different ($p = 0.29$) (Monje *et al.*, 2022).

Lasserre *et al.* (2020) conducted a randomised controlled trial comparing implantoplasty and glycine powder air-polishing in the surgical treatment of peri-implantitis across 31 patients (42 implants). Both groups underwent standard flap surgery, followed by either mechanical implant surface modification or glycine air abrasion. At 3 and 6 months, both treatments showed significant improvements in BoP, SoP, PDs, and relative attachment level (RAL), with no statistically significant differences between groups. Radiographic bone levels remained stable in the implantoplasty group and showed a slight gain in the air-polishing group. The study concluded that both methods are clinically effective in the short term.

Cruz *et al.* (2025) carried out a randomised controlled clinical trial involving 13 patients and a total of 33 dental implants with a follow-up of 24 months. The implants were allocated at the implant level into two treatment groups: 17 implants were assigned to the control group, which underwent conventional surgical access with debridement, while the remaining 16 implants in the test group received adjunctive implantoplasty. In both groups, clinical outcomes showed a general reduction in PD, plaque index (PI), BoP, and a decrease in the width of keratinised mucosa. However, no statistically significant differences were observed between the treatment methods. Based on these findings, the authors concluded that current evidence does not support a clear clinical benefit for the use of implantoplasty in the management of peri-implantitis (Cruz *et al.*, 2025).

A recent meta-analysis conducted by Ramanauskaite *et al.* (2021) evaluated the clinical outcomes associated with implantoplasty in the treatment of peri-implantitis. This analysis incorporated data from the two aforementioned randomised controlled clinical trials (Romeo *et al.*, 2005; Lasserre *et al.*, 2020), assessing clinical parameters such as probing depth (PD) and mucosal level (ML). The weighted mean difference (WMD) in PD at the implant level was found to be -1.11 mm (95% CI: -2.05 to -0.18 , $p = 0.02$), indicating a statistically significant reduction in PD at sites treated with implantoplasty compared to protocols without implantoplasty. The heterogeneity among the included studies was low ($I^2 = 0\%$; $p = 0.429$), indicating consistency in the observed effect. In

addition, the change in ML was minimal and statistically non-significant, with a difference of -0.02 mm (95% CI: -0.56 to 0.53 , $p = 0.95$), suggesting that implantoplasty had no appreciable impact on soft tissue recession.

These findings are consistent with another meta-analysis conducted by Sanz-Martín *et al.* (2021), which also demonstrated a significant additional reduction in PD with a mean decrease of 1.18 mm (95% CI: -1.96 to -0.40 ; $p = 0.005$) when implantoplasty was incorporated into resective surgical protocols compared to protocols without implantoplasty. However, when assessing the impact on gingival recession, the use of implantoplasty led to 0.69 mm (95% CI: 0.31 to 1.08 ; $p < 0.001$) ($n = 12$), compared to 0.56 mm (95% CI: 0.379 to 0.741 ; $p < 0.001$) in the non-implantoplasty group ($n = 22$), suggesting only marginal differences are present between the two approaches (Sanz-Martín *et al.*, 2021).

1.6.2.2.2 Disadvantages of IP

Adverse outcomes from using IP may include potential overheating of the surrounding bone, and subsequent bone necrosis may occur if copious irrigation is not used, along with mucosal pigmentation (Stavropoulos *et al.*, 2019). In addition to clinical disadvantages, mechanical and chemical effects on the dental implant, along with potential cellular insults, may occur, as discussed in the forthcoming sections.

1.6.2.2.2.1 Mass loss of the implant

Sivolella *et al.* (2021) found implantoplasty with the use of tungsten carbide burs led to significantly reduced mean implant volume ($p = 0.002$) and cross-sectional area ($p = 0.001$) when compared to diamond sonic scalers tips when assessed using micro-CT. In addition, the authors found significantly reduced implant mass in the bur group compared to the sonic group ($p < 0.001$) (Sivolella *et al.*, 2021). Tsampli *et al.* (2024) found a larger loss of material in the bur group (-39.2 mg, SD = 4.9 mg) in comparison to an airscaler group (-6.5 mg, SD = 1.4 mg) ($p = 0.001$). Contrastingly, Sahrman *et al.* (2019) showed that in a phantom head model, implant mass loss was not significantly different in relation to the bur protocol used ($p > 0.05$). Diamond burs, followed by

Arkansas stones, showed a mean mass reduction of 0.025 ± 0.009 g, while abrasive stones, followed by silicone polishers, 0.019 ± 0.008 g.

1.6.2.2.2.2 Width reduction and reduced fracture resistance

Camps-Font *et al.* (2023) performed an *in vitro* study on 20 Ti6Al4V dental implants, with 10 of these implants receiving implantoplasty. The authors performed loading of the implants and found that fracture typically occurs perpendicular to the axis of the implant body at the level of the space for the prosthetic screw, representing the narrowest portion of remaining titanium material. The authors explained that external connection implants may be more resistant to fracture in this area due to the increased thickness of materials, which should remain compared to internal connection implants. However, the initial loading of control implants (735N) was higher compared to the test implants (529N), which may have led to an increased amount of implant fractures seen in the control group. Costa-Berenguer *et al.* (2017) showed *in vitro* with all implants that had undergone implantoplasty fractured through the implant body while performing maximum load testing. The control group's fracture pattern differs from that of the implantoplasty group, with half fracturing through the implant body and the remainder fracturing at the level of the abutment screw. The difference in mean maximum compression between the test (896 N; 95% CI; 809.4 - 982.6N) and control implants (880 N; 95% CI; 741.4 - 1018.6N) was not statistically significant ($p = 0.836$).

Chan *et al.* (2013) found *in vitro* that narrow implants (diameter: 3.75mm) had a significantly reduced fracture strength ($321.7\text{N} \pm 21.4$) compared to 4.7mm diameter implants ($430.4\text{N} \pm 26.8$) ($p < 0.001$). In addition, the fracture pattern in the 4.7mm diameter group occurred in the abutment screw, whereas all the 3.75mm implants fractured at the implant platform. A similar pattern of implant fracture was found when performing implantoplasty using a computer-controlled torn for surface modification 3mm apical from the implant neck (Bertl *et al.*, 2021). The implants underwent dynamic loading until failure occurred. Factors which were predictors of reduced maximum implant failure strength had undergone implantoplasty ($p < 0.001$), narrow implants ($p < 0.001$) and were tissue-level in design ($p < 0.001$). In addition, the width reduction of

the implants in this study, after implantoplasty, ranged from 0.13 to 0.16 mm (Bertl *et al.*, 2021).

Leitão-Almeida *et al.* (2020) conducted an *in vitro* study on 48 narrow external connection implants with a 3.5mm diameter and 15mm length. The implants were divided into a control group and groups with increasing crown-to-implant ratio (CIR) (2:1, 2.5, 3:1). Implantoplasty was performed by one experienced operator under magnification and light illumination and was confined to the coronal 7.5mm of the implant. Implant width was assessed using plain film radiographs, and all implantoplasty groups had a significant reduction in width compared to the control ($p \leq 0.05$). The authors found that there was a pattern of reduced maximal compression force (F_{max}) as the crown-to-implant ratio increased. In addition, Gehrke *et al.* (2016) investigated the impact of implant-abutment connection type and its influence on the fracture strength of 4mm diameter implants. They found that after implantoplasty of the coronal 5mm, all implants had a reduced fracture strength compared to their corresponding control implants. Implants with a conical Morse taper connection were shown to have a significantly increased fracture resistance compared to implants with external hexagon and internal hexagon connections. However, implantoplasty was performed using a mechanical lathe and may not accurately represent the width reduction achieved in a clinical setting (Gehrke *et al.*, 2016).

Jorio *et al.* (2021) performed implantoplasty on 30 grade V titanium dental implants in a phantom head model at the upper right first molar site using three instrumentation techniques. No artificial soft tissue models were used, and 6 mm of the implant surfaces were left exposed. Implantoplasty was not performed on the control implants. The overall width reduction of the dental implants was 0.36 ± 0.04 mm after implantoplasty. No implants were fractured after cyclic loading. However, the maximal fracture strength after implantoplasty was significantly lower ($1,737 \pm 165$ N) than that of the control implants ($2,299 \pm 127$ N) (Jorio *et al.*, 2021).

1.6.2.2.2.3 Surface chemistry and corrosion resistance alterations

Schwarz *et al.* (2016) performed implantoplasty on 40 Straumann® implants Straumann® with an initial Standard Plus SLActive surface. Implantoplasty was performed with egg-shaped diamond burs with decreasing grit size and polished with Arkansas stones. Elemental analysis of the implant surfaces after implantoplasty revealed increased amounts of titanium and aluminium and decreased amounts of carbon, oxygen, and sodium compared to control SLA surfaces. Similarly, Sivoilella *et al.* (2021) showed that on implant surfaces that underwent implantoplasty, titanium remained the main surface component after surface modification, although the use of diamond sonic tips led to an increased amount of carbon. In addition, the use of Arkansas bones led to peaks of aluminium in dark spots present on the implant surface. In addition, the titanium disc surfaces treated with implantoplasty using diamond burs showed a decrease in the percentage of oxygen and carbon and an increase in the percentage of titanium on their surface (Toma *et al.*, 2016). While Beheshti Maal *et al.* (2020) found rougher surfaces that underwent implantoplasty had higher levels of carbon and lower titanium content post-treatment.

Interestingly, Camps-Font *et al.* (2023) showed *in vitro* reduction in the corrosion resistance of grade V titanium dental implants with surfaces with implantoplasty compared to implants with untreated minimally roughened surfaces.

1.6.2.2.2.4 Cellular interactions with the surface and titanium particles production

Beheshti Maal *et al.* (2020) performed implantoplasty on grade IV titanium discs with sandblasted and acid-etched surfaces and found that increased surface roughness was negatively correlated with fibroblast growth. All implantoplasty surfaces had significantly more fibroblasts present compared to SLA surfaces after 15 and 30 days. In addition, fibroblasts exhibited an elongated morphology, organised actin filaments and parallel orientation, except for those in SLA surfaces. Schwarz *et al.* (2016) seeded human gingival fibroblasts onto machined, SLA surfaces or implant surfaces treated by implantoplasty. This study found that extending the implantoplasty treatment from 3 to 6mm of the implant surface of bone-level implants was associated with a significant

increase in cell viability ($p < 0.05$). In addition, a higher level of pro-inflammatory cytokine release from fibroblasts was found on the rougher SLA surface than on the implantoplasty-treated surfaces. Similarly, Toma *et al.* (2016) seeded Saos-2 osteoblasts on titanium discs that had surface modification completed with a plastic curette, air-abrasive device titanium brush and implantoplasty with diamond burs. On implantoplasty surfaces after 24 hours, Saos-2 Cells appeared flattened and elongated in contrast to the other treatment surface and SLA control surface, which showed a more polygonal shape. At day 3 and day 6, cell viability was similar among all treatments around, indicating that implantoplasty did not impair cell viability. In addition, alkaline phosphatase, osteoprotegerin and osteocalcin were all expressed similarly amongst treatment groups, showing osteoblast function and proliferation were preserved.

During the implantoplasty process, titanium particles are released into the surrounding tissues (Suárez-López Del Amo *et al.*, 2018). Wu *et al.* (2022) characterised implantoplasty particles when performed by a single experienced operator using a tungsten carbide burs on Straumann®, BioHorizons® and Zimmer® implants. Implants were either titanium-zirconium alloy or grade V titanium (Ti-6Al-4V). Particles mainly were confined within the ultrafine size range (<100 nm). The release of nano and fine particles after implantoplasty of grade V and grade IV titanium implants was also noted by Barrak *et al.* (2020). In this *in vitro* study, human gingival fibroblasts exhibited significantly reduced cell metabolic activity when exposed to grade V titanium particles compared to grade IV titanium. This finding of the effect of grade V particles was also investigated through a systematic review by Willis *et al.* (2021), which found that Ti-6Al-4V particles can have a cytotoxic effect towards gingival fibroblasts (Willis *et al.*, 2021). According to the aforementioned studies, the elemental composition of the particle appears to play a significant role in the cellular response elicited. However, particles $<15\mu\text{m}$ in size may produce a greater pro-inflammatory response (Callejas *et al.*, 2022). However, with the adjunctive use of implantoplasty, there does not appear to be a detrimental inflammatory effect on the tissue clinically (Beheshti Maal and Verket, 2022).

1.6.2.3 Reconstructive surgery

Reconstructive surgery aims to regenerate bone around the implant, achieving re-osseointegration and limiting soft tissue recession (Schwarz *et al.*, 2022; Herrera *et al.*, 2023). The re-osseointegration of previously contaminated implant surfaces has been described in a canine model (Almohandes *et al.*, 2019). Smooth surface implants tend to have a slightly greater extent of re-osseointegration along the implant surface compared to moderately rough implants (Almohandes *et al.*, 2019). Contrastingly, moderately rough implant surfaces are associated with an increased bone-to-implant contact compared to smooth implant surfaces, which have undergone re-osseointegration (Almohandes *et al.*, 2019). The current recommendation is to perform reconstructive surgery with implants affected by peri-implantitis with intra-osseous defects with a defect depth of ≥ 3 mm (Herrera *et al.*, 2023).

This current recommendation is based on a systematic review and meta-analysis performed by Donos *et al.* (2023). A meta-analysis of four studies found that reconstructive surgery with bone grafting materials with or without a membrane, compared to access flap surgery, after 12 months, found an overall change in PD was -0.39 mm (95% CI: -1.16 – 0.38)($p = 0.325$)(Donos *et al.*, 2023). Additionally, another meta-analysis was conducted on the same four studies to assess changes in radiographic mean bone level (Donos *et al.*, 2023). This showed a significant difference in radiographic mean bone levels in favour of reconstructive surgery compared to access flap surgery by -0.75 mm (95% CI: -1.391 – -0.109 mm; $p = .022$)(Donos *et al.*, 2023). The authors noted that there was less buccal recession and a wider keratinised tissue width after reconstructive surgery compared to access flap surgery (Donos *et al.*, 2023). Unfortunately, limited evidence was available regarding long-term implant survival (Donos *et al.*, 2023). However, implant survival at 12 months for access flap surgery ranged from 85.7% to 100%, which is comparable to the 95% to 100% survival rate observed in reconstructive surgery (Donos *et al.*, 2023). Donos *et al.* (2023) found that regardless of the biomaterials used, there was a mean PD reduction ranging from 2 to 4.5mm along with a mean BoP reduction ranging from 44.8% to 86% at 12 months post-therapy. In addition, deeper defects were more likely to result in radiographic defect fill

and 3- and 4-wall defects, resulting in a higher reduction in PD and BoP (Donos *et al.*, 2023; Herrera *et al.*, 2023).

1.6.2.4 Combined surgical technique

A combined surgical technique can be utilised in peri-implant defects when both suprabony and intrabony components are present (Schwarz *et al.*, 2022). In addition to the defect type, the implant position within the bony house should be assessed (Monje and Schwarz, 2022). Implant surfaces that are supra-crestal and that are outside of the bony housing should be treated with implantoplasty, while intrabony defects should be managed with reconstructive techniques (Monje and Schwarz, 2022).

Schwarz *et al.* (2012) performed a randomised controlled study of 24 patients using a combined surgical technique while comparing surface decontamination methods with an Er: YAG laser (n = 10 patients) or plastic curettes, cotton pellets, and sterile saline (CPS) (n = 14 patients). All patients underwent access flap surgery, with the use of implantoplasty in buccal or supra-crestal defects with diamond burs. The surface decontamination method was randomised, and grafting of the infra-bony component of the peri-implant defect was performed using natural bone mineral with a collagen membrane (Schwarz *et al.*, 2012). After 12 months, BoP, PD, mucosal recession and CAL were significantly improved compared to the baseline for both decontamination protocols, with no significant differences observed between the surface treatments ($p > 0.05$). Following 24 months of follow-up, only BoP in both surface decontamination groups remained significantly ($p < 0.001$) reduced while all other parameters regressed. This shows that there may be a gradual return to baseline parameters long-term post-operatively, although reducing the rate of progression of the disease process. Similarly, González Regueiro *et al.* (2021) in a prospective case series of 43 dental implants affected by peri-implantitis that were treated with combined surgical therapy, led to a significant reduction in PD and BoP compared to baseline. However, this study had a small sample size and provided no control group for comparison.

After seven years Schwarz *et al.* (2017) followed 15 of the patients from Schwarz *et al.*

(2012), with 13 of the original patients being uncontactable and a further four patients withdrawing from the study due to pus formation and progressive bone loss. Both Er: YAG laser and CPS decontamination yielded significant clinical improvements in managing advanced peri-implantitis. Mean reductions in BoP exceeded 85% in both groups, and clinical attachment level gains were comparable (CPS: 2.76 mm; ERL: 2.06 mm). While probing depth reduction was greater in the CPS group (2.55 mm) compared to Er: YAG laser treatment (0.74 mm). These findings support the use of a combined surgical technique, although given the large amount of attrition bias, the results should be interpreted with caution.

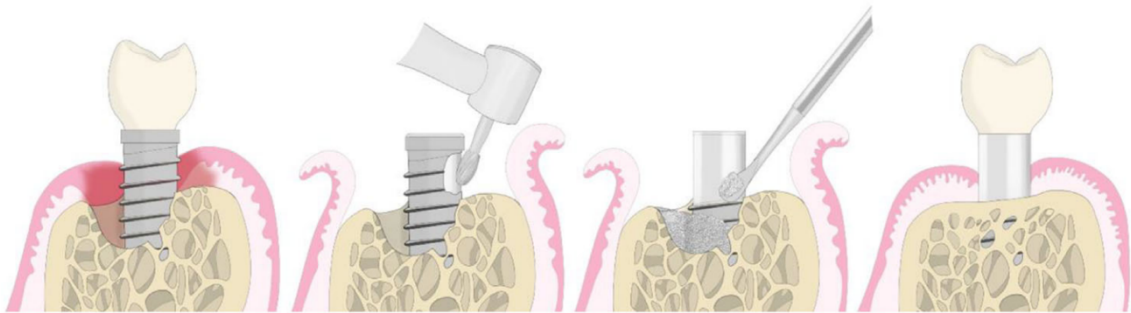


Figure 3: Diagrammatic representation showing the use of implantoplasty during combined surgical therapy in the management of peri-implantitis (Monje and Schwarz, 2022).

1.6.2.5 Adjunctive measures

Air-polishing and Er: YAG laser techniques are not recommended for implant surface decontamination in the surgical treatment of peri-implantitis (Herrera *et al.*, 2023). Similarly, the application of chlorhexidine or photodynamic therapy lacks sufficient support for routine clinical use in this context. However, titanium brushes may offer a viable option for mechanical decontamination during surgery. Evidence remains limited regarding the effectiveness of local antibiotics as adjunctive agents in the surgical management of peri-implantitis (Herrera *et al.*, 2023).

1.7 Association of bacterial adhesion and surface roughness

Plaque formation can occur through four phases: transport to the surface, initial adhesion, attachment, and colonisation, followed by plaque maturation (Teughels *et al.*, 2006). The initial adhesion of bacteria starts at locations initially sheltered against shear forces, allowing reversible attachment to become irreversible (Teughels *et al.*, 2006). Rough surfaces exposed to the oral environment are challenging to clean, and a rapid regrowth of biofilm occurs from the growth of existing biofilm rather than from recolonisation of the surfaces (Quirynen *et al.*, 1996). The non-shedding nature of implant surfaces may contribute to the development of thick biofilm (Teughels *et al.*, 2006). These initial colonisation dynamics highlight the importance of understanding how specific implant surface characteristics influence microbial adhesion and subsequent biofilm development.

Fürst *et al.* (2007) investigated the submucosal microbiota colonisation after implant placement with transmucosal healing in 14 subjects, totalling 17 titanium implants. The investigators detected colonisation of the peri-implant site with *P. gingivalis*, *T. forsythia*, *T. denticola*, *P. intermedia*, and *A. actinomycetemcomitans* occurring within a 30-minute window after implant placement using the checkerboard DNA-DNA hybridisation method (Fürst *et al.*, 2007). In addition, at weeks 8 and 12 post-implant placement, there was a significantly increased bacterial load of *P. gingivalis* ($P < 0.05$), *T. forsythia* ($P < 0.01$), and *T. denticola* ($P < 0.001$) (Fürst *et al.*, 2007). A systematic review and meta-analysis by Carvalho *et al.* (2023) included a total of 12 cross-sectional studies with 1233 patients and 1513 implants. The presence of *S. epidermidis* (OR = 10.28 [CI: 1.26–83.98]), *F. nucleatum* (OR = 7.83 [95% CI: 2.24–27.36]), *T. denticola* (OR = 6.11 [95% CI: 2.72–13.76]), *T. forsythia* (OR = 4.25 [95% CI: 1.71–10.57]), *P. intermedia* (OR = 3.79 [95% CI: 1.07–13.35]), and *P. gingivalis* (OR = 2.46 [95% CI: 1.21–5.00]) was associated with peri-implantitis (Carvalho *et al.*, 2023). However, due to the cross-sectional nature of these studies, the presence of these bacteria acts as a risk indicator for peri-implantitis and not a risk factor, as causality cannot be determined.

Microbes associated with peri-implantitis are not eliminated after non-surgical or

surgical modalities of treatment, although the microbial load is reduced (Di Spirito *et al.*, 2024). Interestingly, peri-implantitis rates appear to increase as the surface roughness of the implant body increases (Jordana *et al.*, 2018). This may be due to an increased retention of dental plaque on the rough intra-oral surfaces (Bollen *et al.*, 1997). These observations suggest that implant surface texture plays a significant role in long-term microbial persistence and insult to the peri-implant tissues. However, it has been shown through qPCR, checkerboard and culture techniques that overall, machined “turned” implant surfaces and moderately rough implant surfaces produce no difference in subgingival microbiota at one year post-implantation (Quirynen and Van Assche, 2012). A review by Bollen *et al.* (1997) found that bacterial adhesion to intraoral hard surfaces was reduced when the arithmetic average surface roughness (Ra) was $\leq 0.2 \mu\text{m}$. When the surface roughness exceeded this level, dental plaque gathered spontaneously. However, Bollen *et al.* (1997) focused on the surface roughness found in teeth, implant abutments, amalgam and composite restorations, and acrylic resins, which may not be representative of dental implant surfaces. This is because factors influencing bacterial adhesion to surfaces also include material chemical composition, surface energy, and wettability (Mabboux *et al.*, 2004). These factors indicate that surface roughness may be only one of several variables governing bacterial colonisation on dental implants.

1.7.1 *In vitro* studies

In vitro studies in the literature have assessed the surface roughness of titanium surfaces and its impact on microbial adherence. Pereira da Silva *et al.* (2005) investigated the attachment of *Streptococcus sanguis* on titanium discs of varying surface roughness levels. Group 1 had machined surfaces, with a Ra of $0.17 \mu\text{m} \pm 0.01$, while Groups 2 and 3 were titanium surfaces with a surface roughness of Ra of $1.14 \mu\text{m} \pm 0.15$ and $3.17 \mu\text{m} \pm 0.23$, respectively. Increasing surface roughness led to an exponential increase in bacterial cell presence, with Group 1 retaining 49×10^3 cells and Group 2 and 3 retaining 11×10^4 and 35×10^5 , respectively (Pereira da Silva *et al.*, 2005). This trend demonstrates a direct correlation between increased surface irregularity and enhanced microbial retention in controlled laboratory conditions.

Similarly, the adherence of *P. gingivalis* on roughened titanium implant surfaces with or without a hydrophilic surface modification was examined by Amoroso *et al.* (2006). This study had four groups of surface roughness: very smooth ($34.57 \text{ nm} \pm 5.79$), smooth ($155 \text{ nm} \pm 33.36$), rough ($223.24 \text{ nm} \pm 9.86$), and very rough ($449.42 \text{ nm} \pm 32.97$). The very smooth surface group had significantly less *P. gingivalis* adhesion compared to the other test groups ($p = 0.001$), while no significant differences were found between the hydrophobic and hydrophilic surfaces ($p = 0.273$) (Amoroso *et al.*, 2006). These findings suggest that surface topography plays a more prominent role than hydrophilicity in influencing bacterial attachment for this species.

Al-Radha *et al.* (2012) used a saliva pellicle model on titanium surfaces with differing roughness levels to evaluate bacterial adherence. The polished titanium group (PT) had a Ra of $0.034 \pm 0.004 \text{ }\mu\text{m}$, while the zirconia blasted (TBZ) titanium and zirconia blasted and acid-etched group (TBZA) had Ra values of $0.158 \pm 0.003 \text{ }\mu\text{m}$ and $0.150 \pm 0.005 \text{ }\mu\text{m}$, respectively. In contrast to the aforementioned studies, *S. mitis* showed less adherence to the rougher TBZ surfaces compared to the polished PT surfaces in the saliva pellicle model. The adhesion of *P. nigrescens* was not significantly different across the surfaces. However, *S. mitis* and *P. nigrescens* were most adherent to the TBZA surface. Interestingly, this study demonstrated that the use of a saliva pellicle reduced the percentage of adhesion of *S. mitis* and *P. nigrescens* on all surfaces compared to when it was not used (Al-Radha *et al.*, 2012). This highlights the influence of saliva on the modulation of bacterial behaviour, which may be independent of surface roughness alone.

A multispecies biofilm model was used by Bermejo *et al.* (2019) to assess biofilm formation on dental titanium implants with differing surface topographies. Minimal-roughness (Sa $0.5\text{--}1\text{ }\mu\text{m}$) and moderate-roughness (Sa $1\text{--}2\text{ }\mu\text{m}$) surface implants were utilised. After an incubation period of 96 hours, significantly higher values of total bacteria ($p = 0.036$), *F. nucleatum* ($p = 0.013$), and *A. actinomycetemcomitans* ($p = 0.002$) were found on the moderately rough implant surfaces compared to the minimally rough surfaces (Bermejo *et al.*, 2019). This further supports the notion that even moderate

increases in roughness can enhance colonisation by pathogenic species. Fröjd *et al.* (2011) found using *Streptococcus sanguinis*, *Actinomyces naeslundii*, and *Lactobacillus salivarius* in an *in vitro* model that there was a seven-fold higher adhesion to roughened titanium surfaces of Sa 1.0-2.0µm when compared to turned titanium surfaces (Sa = 0.18µm) after two hours. The investigators hypothesised that the increased adhesion of bacteria was, in part, due to the protective topographic features of the rough surface against shear forces. However, over 16 hours, surface roughness did not appear to affect the total volume of the biofilm between turned and roughened titanium surfaces (Fröjd *et al.*, 2011). Thus, while surface topography may affect early adhesion, its long-term impact on total biofilm volume appears to be less significant. Almaguer-Flores *et al.* (2012) found that for surface roughness on titanium discs with pretreatment (Ra < 0.2µm), acid-etched (Ra < 0.8µm), and sandblasted and acid-etched (Ra = 4µm) surfaces when human saliva was used, total bacteria counts were higher on rougher surfaces compared to the pretreatment surface ($p < 0.05$). Additionally, the authors found significantly higher total bacterial counts on the titanium discs with a culture medium present rather than human saliva as a medium. Interestingly, this finding is similar to that of Al-Radha *et al.* (2012). These comparative observations suggest that both surface roughness and environmental factors significantly influence microbial adherence. However, the use of culture medium instead of saliva may affect the transferability of the results regarding total bacterial counts and bacterial adhesion to an *in vivo* model. Therefore, while *in vitro* studies provide essential insight, extrapolating these findings to clinical scenarios requires cautious interpretation.

Toma *et al.* (2018) investigated the use of decontamination techniques for *S. gordonii* on titanium discs and the recolonisation of those treated surfaces *in vitro*. The investigators found significantly improved biofilm elimination using Perio-Flow®, Ti-Brush®, and IP performed with diamond round burs when compared to Ti control and the use of plastic curettes ($p < 0.001$). The resulting surface roughness was significantly lower in the implantoplasty group, Ra 0.98 ± 0.12 µm and Rz 7.26 ± 0.022 µm, compared to the other surfaces ($p < 0.01$). Recolonisation of *S. gordonii* on the treated titanium discs using saliva was reduced significantly compared to control for Perio-Flow® ($p <$

0.01), Ti-Brush® ($p < 0.001$), and IP ($p < 0.001$) (Toma *et al.*, 2018). In addition, IP had the lowest levels of reattachment of *S. gordonii* compared to Perio-Flow® and Ti-Brush®, although this difference was not statistically significant ($p > 0.05$) (Toma *et al.*, 2018). This study demonstrates the importance of achieving low surface roughness after decontamination of titanium surfaces to reduce bacterial adhesion and recolonisation.

1.7.2 *In vivo* studies

Quirynen *et al.* (1993) found that significantly more plaque accumulated on rough implant abutments compared to smooth abutments, 50.8×10^4 and 2.6×10^4 c.f.u., respectively. The abutments were sampled after being in function intra-orally for three months. The smooth and rough abutments had a Ra of $0.35 \pm 0.03 \mu\text{m}$ and $0.81 \pm 0.1 \mu\text{m}$, respectively. Later *in vivo* studies by the same research group confirmed that a reduction of surface roughness under a “threshold Ra” of $0.2 \mu\text{m}$ had no significant impact on supra- or subgingival plaque composition (Bollen *et al.*, 1996; Quirynen *et al.*, 1996). Elter *et al.* (2008) evaluated the supra- and sub-gingival plaque in 11 patients with 15 healing abutments inserted with differing surface treatments after 14 days. The surfaces tested were sandblasted (Ra = $0.9 \mu\text{m}$), ground (Ra = $0.4 \mu\text{m}$), acid-etched (Ra = $0.3 \mu\text{m}$), and control (Ra = $0.2 \mu\text{m}$) (Elter *et al.*, 2008). Biofilm formation was present and displayed as percentage coverage of abutment: sandblasted ($47.4\% \pm 32.4$), ground ($18.6\% \pm 31.4\%$), acid-etched ($15.6\% \pm 18.7\%$), and control ($5.7\% \pm 14.4\%$) (Elter *et al.*, 2008). Control surfaces of abutments had significantly less supra-gingival plaque accumulation compared to sandblasted ($p = 0.012$), ground ($p = 0.034$), and acid-etched ($p = 0.028$) abutments (Elter *et al.*, 2008). Interestingly, the subgingival differences in biofilm formation between abutment surfaces were not statistically significant ($p > 0.05$) (Elter *et al.*, 2008). This may be due to the abutments containing the same surfaces and thus sharing the same sulcus and subgingival microbiome or due to the short duration of the study. This study demonstrates that less supra-gingival plaque accumulation occurs on surfaces with a Ra of $0.2 \mu\text{m}$ compared to those with increased surface roughness.

Azzola *et al.* (2020) investigated the effects of IP on biofilm formation, with one

volunteer wearing an intra-oral tray housing three implants with moderately rough surfaces and three implants treated with IP. No plaque control measures were performed on the housed implants. After 5 days, the IP surfaces had significantly less plaque formation ($16\% \pm 0\%$) compared to moderately rough surfaces ($65.00\% \pm 7.07\%$). Additionally, biofilms that formed on IP surfaces were less mature than those on moderately rough surfaces (Azzola *et al.*, 2020). This finding is similar to that of Bürgers *et al.* (2010). The investigators used six patients with removable appliances, each appliance carrying two sandblasted and acid-etched Ra of $0.95\ \mu\text{m}$ and two machined titanium discs, Ra of $0.15\ \mu\text{m}$, with participants wearing the appliances for 12 hours (Bürgers *et al.*, 2010). Machined surfaces had significantly fewer total microbes present compared to roughened surfaces ($p = 0.004$) (Bürgers *et al.*, 2010). The authors advised that any parts of an implant exposed to the oral cavity should be smoothed and polished to reduce plaque accumulation (Bürgers *et al.*, 2010). Simion *et al.* (2016) performed an analysis of an explanted implant after being affected by peri-implantitis. The authors found the smooth surface of the abutment had minimal plaque accumulation, while directly under the abutment-implant harboured aggregates of bacteria (Simion *et al.*, 2016). The moderately roughened surface of the implants had large amounts of biofilm, mainly consisting of rods and filamentous bacteria (Simion *et al.*, 2016). The authors concluded that if regenerative techniques were to be used, definitive surface decontamination of the implant should be performed (Simion *et al.*, 2016).

Geremias *et al.* (2017) published a case report in which they treated three implants in a single patient with three different approaches: 1) IP, 2) open flap debridement with citric acid decontamination and 3) open flap debridement alone. After 4 months, these treatments were deemed unsuccessful, and the implants were explanted. The authors found less planktonic growth of *S. mutans* on the implants which underwent IP and open flap debridement with citric acid decontamination after inoculation (Geremias *et al.*, 2017). Similarly, El Chaar *et al.* (2020) conducted an *in vivo* study comparing seven implants of differing brands that failed due to peri-implantitis. These implants were then subsequently explanted, and the surface was decontaminated *ex vivo*. IP using a fine

diamond bur followed by a carbide bur showed complete removal of biofilm, while chemical agents (saline, hydrogen peroxide 3%, phosphoric acid gel 35%, chlorhexidine gluconate 0.12% and citric acid 40%) showed no removal of biofilm (El Chaar *et al.*, 2020). However, particle abrasion with sodium bicarbonate, the use of a titanium brush and Er: YAG lasers showed some removal of biofilm deposits from the implant surface. This study shows that complete decontamination of the implant surface from biofilm may only be achievable through the use of implantoplasty (El Chaar *et al.*, 2020).

Overall, these *in vivo* studies demonstrated that microbial adhesion and biofilm accumulation were less on smoother titanium implant surfaces and surfaces modified by IP. This conclusion aligns with the systematic review performed by Burgueño-Barris *et al.* (2021) which showed that IP appeared to reduce biofilm adhesion and regrowth on treated implant surfaces. This finding supports that of Bollen *et al.* (1997), that a Ra of 0.2µm on restorative material facilitates the formation of biofilm, and below this threshold, the level of bacterial load is not affected. These findings were later supported by another systematic review by Teughels *et al.* (2006).

1.8 Implant surface roughness after implantoplasty

1.8.1 Surface roughness of discs for tabletop models

Tawse-Smith *et al.* (2016) conducted a study on 40 titanium grade IV discs, consisting of 20 discs with a machined surface and 20 with roughened surfaces. Implantoplasty was performed on these surfaces using regular and super fine grit diamond burs, along with two silicone polishers, utilising a handpiece connected to a controlled pressure device. The authors found that the final surface roughness after implantoplasty was not significantly different between the machined surfaces (Ra; 4.00 μm) and moderately roughened surfaces (Ra; 4.50 μm) ($p = 0.095$) (Tawse-Smith *et al.*, 2016). This finding suggests that the initial surface roughness of a disc may not impact the final result achieved by implantoplasty.

Beheshti Maal *et al.* (2020) performed IP on titanium grade IV discs with either three diamond burs (105 μm , 40 μm and 8 μm grit) or two tungsten carbide cutting burs followed by either silicone polishers or Arkansas stone polishers. Forty-eight titanium grade IV discs were used, with 36 discs being moderately rough, sandblasted and acid-etched as part of the treatment group, and in the control groups, six discs were sandblasted, acid-etched, and six discs were polished titanium. Implantoplasty was performed under irrigation for one minute. Surface roughness was measured using a 3D optical profilometer. The authors found that either tungsten carbide burs or diamond burs supplemented with silicone polishers achieved the lowest surface roughness results in terms of Sa and Sz. However, these bur protocols were significantly rougher than those of the polished titanium discs. Additionally, when diamond burs were used, the surface exhibited more irregular and non-linear grooves compared to tungsten carbide burs. These grooves diminished with the polishing of silicone burs or Arkansas stones. These results highlight the importance of post-bur polishing protocols in reducing surface irregularities introduced during mechanical instrumentation.

Toma *et al.* (2018) assessed the effectiveness of various decontamination protocols using 250 moderately rough titanium discs colonised with *S. gordonii* using plastic curettes, an air powder abrasive system, a titanium brush, or IP with a diamond bur.

Contact profilometry indicated that the diamond bur group achieved a Ra of $0.98 \pm 0.12 \mu\text{m}$ and an Rz of $7.26 \pm 0.022 \mu\text{m}$, which were significantly lower than those of all other surface decontamination protocols ($p < 0.01$) (Toma *et al.*, 2018). This study adds to the evidence base by comparing implantoplasty not only as a surface modification method, but also as a biofilm removal strategy. In addition, Vierling *et al.* (2024) found that tungsten carbide burs produced a higher mean surface roughness Ra of $2.4 \pm 0.4 \mu\text{m}$ compared to diamond burs of $1.8 \pm 0.3 \mu\text{m}$ on titanium acid-etched discs using a contact profilometer. This study used 64 titanium and 64 zirconia discs, with 32 in each group being either sandblasted and acid-etched or machined surfaces. Discs were treated using a diamond bur, carbide bur, ultrasonic scaling device, or an airflow device. For the implantoplasty, the handpieces were attached to a jig, allowing for a standardised angle and pressure application. The burs were used for a total duration of 60 seconds and performed by a single operator, and no polishing was performed (Vierling *et al.*, 2024). The absence of a polishing stage in this study underscores the critical role of finishing protocols in achieving clinically acceptable smoothness.

Yildiz *et al.* (2022) used 60 discs of grade IV titanium to investigate surface roughness following different IP protocols. Forty-eight discs had a sandblasted large-grit acid-etched surface, while 12 discs had a turned surface. The turned surface group was designated as the positive control group, while 12 discs from the SLA group served as the negative control. Three IP protocols, each with 12 discs, were involved, comprising two tungsten carbide bur groups (C1 and C2) using burs from different manufacturers and a diamond bur group (D) consisting of three burs of decreasing grit. Polishing was performed in the tungsten carbide groups (C1+p and C2+p) and the diamond group (D+p) using a silicone polisher. Surface roughness was measured using a contact stylus profilometer before and after polishing in each treatment group. The authors found that the surface roughness reduced significantly in all bur groups after polishing with silicone polishers ($p < 0.01$). The Ra for C1+p ($0.14\mu\text{m}$) and C2+p ($0.13\mu\text{m}$) groups were significantly lower than the D+p group ($0.27\mu\text{m}$) ($p < 0.001$). The C1+p and C2+p groups achieved significantly lower surface roughness than the control turned surface ($0.22\mu\text{m}$) ($p < 0.001$). The results for Rz followed a similar pattern; the C1+p ($0.69 \mu\text{m}$) and C2 +p

(0.69 μm) groups were significantly lower than the D +p group (1.20 μm) ($p < 0.001$). Additionally, the C1+p and C2 +p groups achieved significantly lower Rz than the negative control SLA surface (1.79 μm) (Yildiz *et al.*, 2022). This study demonstrates that the final polishing after IP with a silicone polisher will further reduce surface roughness and that carbide burs will provide an overall reduced Ra and Rz compared to diamond burs (Yildiz *et al.*, 2022).

These studies demonstrate that when IP is performed on titanium discs, the selection of bur and subsequent polishing play a crucial role in determining the final surface characteristics (Tawse-Smith *et al.*, 2016; Toma *et al.*, 2018; Beheshti Maal *et al.*, 2020; Yildiz *et al.*, 2022; Vierling *et al.*, 2024).

1.8.2 Surface roughness of implants for tabletop models

Several *in vitro* studies have used dental implants to replicate the substrate being reduced intra-orally in patients during IP. Meier *et al.* (2012) utilised 22 implants with moderately rough, sandblasted, and acid-etched surfaces, divided into 11 surface treatment burs protocol groups with varying shapes and cutting designs. Two researchers performed the IP procedures, one on each side of a single implant. Surface roughness was measured using tactile profilometry over a 4.80mm length at three different points per instrumented surface. They found that conical-shaped tungsten carbide burs provide the smoothest surface, while the roughest results were obtained using a rounded tungsten carbide bur. Round tungsten carbide burs with notches on their blades (burs 4, 5, 6) produced large Ra and Rz values, while carbide burs with round ends that have no notches (burs 1, 2, 3) yielded comparable Ra and Rz values. However, Ra or Rz values were only available diagrammatically and individual numerical figures were not available for comparison. The amount of time required was not associated with a lower Ra ($p = 0.44$) or lower Rz values ($p = 0.83$) (Meier *et al.*, 2012). This study highlights that bur type and shape, along with blade design, can significantly influence the final surface roughness following IP (Meier *et al.*, 2012).

de Souza Júnior *et al.* (2016) found no significant difference in final surface roughness

after the use of different bur protocol on 36 implants with dual-etched surfaces; diamond bur (Ra: 4.13 μ m), tungsten carbide bur (Ra: 4.88 μ m), and multi-laminar (Ra: 5.01 μ m) bur groups ($p > 0.05$). The control group, which was a machined prosthetic abutment, exhibited a significantly smoother surface roughness (Ra: 1.92 μ m) compared to the diamond bur, tungsten carbide bur and multi-laminar bur groups ($p < 0.05$). A standardised pressure of 100g was applied during IP, and all implants received only one Ra measurement of a 5mm linear portion of the assessed surface. Furthermore, the total procedure time required varied significantly between groups (diamond: 50 seconds, tungsten carbide: 40 seconds, multilaminar: 30 seconds) ($p < 0.05$). In addition to surface roughness measurements, the authors noted no significant difference in bone temperature change among the bur groups measured in the bone (diamond; 1.38°C, tungsten carbide; 0.91°C, multilaminar; 0.97°C) ($p > 0.05$). The implant temperature increase was significant among groups, with the diamond bur group showing the most significant increase (diamond; 4.67°C, tungsten carbide; 1.12°C, multilaminar; 2.49°C) ($p < 0.05$) (de Souza Júnior *et al.*, 2016). These findings introduce thermal considerations, emphasising that bur choice may influence not only roughness but also procedural safety in relation to local thermal changes.

Ramel *et al.* (2015) conducted an *in vitro* study on 42 moderately rough sandblasted and acid-etched dental implants with a 6mm of the roughened surface exposed. IP was performed with diamond bur protocols of varying grit sizes with polishing completed with either silicone burs or Arkansas stones (Ramel *et al.*, 2015). Ra and Rz were measured with a stylus profilometer. The protocol that achieved the smoothest result included diamond burs with grits of 106, 40, and 15, followed by Brownie and Greenie silicone polishers (Ra: 0.32 $\pm$ 0.14 μ m; Rz: 2.31 $\pm$ 0.95 μ m) ($p < 0.001$). This treatment group took 21 $\pm$ 4 minutes to complete. However, the surface roughness achieved by this protocol was significantly rougher compared to the smooth polished implant neck as the negative control (Ra 0.10 $\pm$ 0.01 μ m; Rz 0.81 $\pm$ 0.19 μ m). Due to the large amount of debris produced by silicone polishers and potential surgical site contamination, the authors recommended using Arkansas stone polishers in clinical practice (Ramel *et al.*, 2015). This underscores the trade-off between surface smoothness and clinical

practicality, especially with regard to polishing debris.

Costa-Berenguer *et al.* (2017) completed IP on the coronal 6.5mm of ten grade IV titanium dental implants with moderately rough sandblasted and acid-etched surfaces using an oval-shaped tungsten carbide bur, followed by two silicone carbide polishers. Ten implants with the same surface treatment were utilised as controls. IP was performed freehand by one experienced clinician under 2.5x magnification with light illumination. The pressure and the number of strokes of the bur were not standardised to increase the generalisability of the results. A confocal optical microscope was used to measure three areas of each test and control implant for surface roughness. The test surfaces achieved a Sa of $0.1 \pm 0.02 \mu\text{m}$ and a Sz of $3.67 \pm 1.28 \mu\text{m}$, which were significantly lower than those of the control surfaces ($p < 0.005$). Interestingly, no significant differences in surface roughness were found in the coronal, middle, or apical areas of the implant where IP had been performed ($p < 0.05$). The total mean time for each implant was 10 min 48 seconds $\pm$ 1 min 22 seconds (Costa-Berenguer *et al.*, 2017). This study illustrates that IP can yield uniformly smooth surfaces across the implant, even with non-standardised operator pressure.

Camps-Font *et al.* (2023) confined IP to the coronal 5mm of the implants included in their study. IP was performed on 10 tapered Ti6Al4V (grade V titanium) implants with a moderately rough surface using the same bur protocol described in Costa-Berenguer *et al.* (2017). A single experienced clinician conducted the procedure under 2.8x magnification and light illumination. However, the Sa of $0.49 \pm 0.16 \mu\text{m}$ and Sz of $8.19 \pm 4.16 \mu\text{m}$ were markedly higher compared to the aforementioned study (Camps-Font *et al.*, 2023). This may have been due to the use of differing titanium grades of implants between the studies or the operator's experience with the procedure. This inter-study variation suggests that factors such as titanium composition and clinician technique can significantly influence final outcomes.

Sivolella *et al.* (2021) used 18 grade IV titanium dental implants, divided equally among egg-shaped tungsten carbide burs, a sequence of two torpedo-shaped diamond sonic

tips, and a control group. Both treatment groups were polished with Arkansas burs. The coronal 6mm of the implants underwent IP performed by one expert clinician under magnification. The pressure applied during the procedure was not standardised. Stylus profilometry measured the Ra and Rz of the implants with four area measurements of 2.2 mm x 1 mm in the modified area of the test implants. After polishing, there was no significant difference between the Ra of the tungsten carbide group ($0.54 \pm 0.06 \mu\text{m}$) and the sonic group ($0.60 \pm 0.05 \mu\text{m}$) ($p = 0.15$). Additionally, there was no significant difference found between the Rz of the tungsten carbide group ($2.78 \pm 0.30 \mu\text{m}$) and the sonic group ($3.03 \pm 0.34 \mu\text{m}$) after polishing ($p = 0.23$) (Sivolella *et al.*, 2021). This suggests that sonic instruments may serve as a viable alternative to traditional rotary tools, although further comparative data are needed.

Tsampli *et al.* (2024) used 30 implants, grade IV titanium implants, which were divided into three treatment groups: diamond bur, non-diamond-coated sonic tips (air scaler), and control. IP was performed using a universal testing device that enabled control over implant position and the application of a constant pressure of $1 \pm 0.1\text{N}$. Following the surface treatment, a tactile profilometer conducted a total of 12 measurements of Ra and Rz on the treated part of each implant, with the implant rotated by 30° after each line. A 3D surface analysis was also performed. The diamond burs achieved a Ra of $0.42 \pm 0.03 \mu\text{m}$ and an Rz of $3.05 \pm 0.36 \mu\text{m}$, while the Sa and Sz were recorded as $0.36 \pm 0.03 \mu\text{m}$ and $3.88 \pm 0.78 \mu\text{m}$, respectively. The air scaler achieved lower Ra and Rz values of $0.33 \pm 0.06 \mu\text{m}$ and $2.80 \pm 0.53 \mu\text{m}$, respectively. Additionally, this was reflected in a lower Sa value of $0.25 \pm 0.11 \mu\text{m}$ and a Sz value of $2.86 \pm 1.06 \mu\text{m}$. The air scaler achieved a significantly lower Ra ($p = 0.003$) and Sa ($p = 0.002$) compared to the diamond bur group. In addition, the Sz was significantly lower for implants modified by the air scaler group ($p = 0.039$). However, no significant differences were noted for Rz values between the treatment groups ($p = 0.421$) (Tsampli *et al.*, 2024). This novel instrumentation approach offers promise in achieving lower roughness values, although its clinical applicability remains to be validated.

Collectively, these *in vitro* studies demonstrated that IP consistently reduced the surface

roughness of moderately rough dental implants, but the degree of smoothness achieved is highly dependent on the bur protocol or instrument used.

1.8.3 Surface roughness of implants in a phantom head

Rimondini *et al.* (2000) investigated the effect of diamond and carbide burs on 22 plasma-spray-coated implants within a phantom model. Each implant surface was divided into four sections. The authors employed different-shaped and variably bladed tungsten carbide burs and diamond burs of various grits (30 μm , 15 μm , and 8 μm). A stylus profilometer measured the Ra and Rz for surface topography assessment over two lengths of 1.5mm in each section, with the mean of both measurements used for statistical analysis. IP was performed freehand by a single operator, applying an average lateral pressure of 0.43 N. All bur types resulted in a significantly smoother surface for both Ra and Rz when compared to the treated baseline implant surface ($p < 0.001$). The most effective protocols included a sequence of diamond burs with grit sizes of 30 μm and 15 μm (Ra: 1.04 ± 0.14 ; Rz: 4.86 ± 0.57), along with a combination of carbide burs featuring eight blades, followed by those with 16 blades (Ra: 1.16 ± 0.26 ; Rz: 4.04 ± 0.83) (Rimondini *et al.*, 2000). However, no polishing with silicone polishers took place in this study. This early phantom model study offered a foundational insight into how different bur types affect surface roughness, although the absence of polishing limits its clinical relevance.

Later, Sahrman *et al.* (2019) performed an *in vitro* study using phantom heads to mimic several factors present in a clinical setting with 30 grade IV titanium implants. This study utilised stone casts with implants placed in the 1-6 or 2-6 sites. Each implant had 6mm of roughened surface exposed, and a horizontal defect was present. The model included adjacent teeth, but a soft tissue model was not used. For the IP procedure, Group 1 used diamond burs of decreasing grit size (106 μm to 40 μm), followed by polishing with Arkansas stone burs. Group 2 employed silicon carbide stones, followed by Arkansas stone and silicone polishers. A maximum timeframe of 15 minutes was allocated for the IP procedure, with six minutes designated for the initial burs and a further nine minutes for polishing. Surface roughness for Group 1 reported a Ra of $0.76 \pm 0.14 \mu\text{m}$ while Rz

was $4.12 \pm 0.72 \mu\text{m}$. For Group 2, the Ra was $0.38 \pm 0.15 \mu\text{m}$, and the Rz was $1.87 \pm 0.69 \mu\text{m}$. The differences in Ra and Rz between Group 1 and Group 2 were significant ($p < 0.001$) (Sahrman *et al.*, 2019). This study demonstrated that the bur types used along with polishing protocols directly influence the final roughness when operating under clinically simulated conditions.

Burgueño-Barris *et al.* (2023) Investigated whether clinical factors impact post-IP surface roughness within a phantom head model. A total of 60 grade V titanium implants were placed with 5mm of roughened implant surface exposed in 20 resin casts and mounted in a phantom head. Implants were located in either favourable situations (maxillary incisors with no adjacent teeth) or unfavourable situations (mandibular molars with adjacent teeth) using a soft tissue model to replicate a clinical scenario. IP was performed with an oval tungsten carbide bur and two silicone carbide polishers, taking a median time of 6 minutes and 40 seconds. A confocal optical microscope was used to assess the Sa and Sz of the treated surface. This study showed that IP significantly reduced surface roughness after the treatment (Sa: $0.60 \mu\text{m}$, SD; 0.14; Sz: $1.83 \mu\text{m}$ SD 0.10) compared to before the procedure (Sa: $1.83 \mu\text{m}$, SD 0.10; Sz: $37.78 \mu\text{m}$ SD 0.35) ($p < 0.001$) (Burgueño-Barris *et al.*, 2023). However, the resultant surface roughness after IP was significantly rougher than polished control surfaces (Sa: $0.24 \mu\text{m}$, SD 0.01; Sz: $4.46 \mu\text{m}$, SD 0.15) ($p < 0.001$). Surface roughness was significantly higher in the unfavourable situation than in the favourable group (Sa: MD = $0.16 \mu\text{m}$; 95% CI = 0.10 to 0.21; Sz: MD = $4.86 \mu\text{m}$; 95% CI = 3.42 to 6.29), along with significantly longer treatment times ($p < 0.05$). Furthermore, the presence of a crown on the implants led to an increased number of residual threads after IP (OR = 7.0; 95% CI = 3.5 to 13.99; $p < 0.001$) (Burgueño-Barris *et al.*, 2023). This study highlighted that restricted access is associated with increased surface roughness following IP, indicating that anatomical constraints at specific sites may hinder the procedure's efficacy.

The literature shows significant variation in IP bur protocols used in studies. The overall pattern indicates that tungsten carbide burs produce smoother surfaces compared to diamond burs. However, after a polishing protocol is applied, this difference diminishes,

although the use of tungsten carbide burs, even after polishing, still results in lower surface roughness compared to diamond burs. Novel sonic scaler tips show a promising alternative to the use of burs for IP; however, further studies that replicate a clinical setting are required before their use is suggested for this purpose.

The surface roughness achieved from IP *in vitro* studies may differ from that in clinical settings. However, there are no studies in the literature which investigate this. Multiple studies have evaluated the final surface roughness of implants after IP in a phantom head model (Rimondini *et al.*, 2000; Sahrman *et al.*, 2019; Burgueño-Barris *et al.*, 2023). The phantom head model allows many aspects of a clinical setting to be transferred and may provide a more accurate representation of the surface topography likely to be achieved clinically when IP is performed intra-orally. Currently, there are no studies comparing the surface roughness found in a tabletop setting and in a phantom head setting to see if they are comparable or different. The aim of our study is to investigate whether access to the implant during IP plays a potential role in the final surface roughness achieved in a phantom head model when compared to a tabletop model.

2 Materials and methods

This study was conducted and reported in alignment with the modified Consolidated Standards of Reporting Trials (CONSORT) guidelines for *in vitro* studies in dental materials (Faggion, 2012) (Appendix 2).

2.1 Aims

The aim of this *in vitro* study was to examine whether performing IP in a simulated clinical environment using a phantom head yields comparable outcomes to performing the procedure under standardised conditions on a tabletop model.

The null hypothesis was that IP performed in a simulated clinical environment would result in surface roughness (Ra and Rz) of the implant that would be comparable to that achieved using the tabletop method.

The alternative hypothesis was that there would be a difference in surface roughness (Ra and Rz) between the implant surfaces of the phantom head and the tabletop.

Additionally, material loss of the dental implants after IP when compared between the simulated environments was evaluated. Finally, the influence of implant anatomy and implant preparation site on material loss and surface smoothness following IP was also evaluated.

2.2 Power calculation

Given the novelty of this study, no existing data is available for direct sample size estimation. However, a power calculation was performed to get an approximate estimation of the sample size required. We considered the published results by Sahrman *et al.* (2019), which assessed surface roughness (Ra and Rz) between two different bur protocol for IP in implants that were placed in casts with IP performed in phantom heads.

Ra: We are planning a study of a continuous response variable from independent control and experimental subjects with 1 control(s) per experimental subject. In a previous study, the response within each subject group was normally distributed with a standard deviation 0.145. If the true difference in the experimental and control means is 0.38 μm , we will need to study 4 experimental subjects and 4 control subjects to be able to reject the null hypothesis that the population means of the experimental and control groups are equal with probability (power) 0.8. The Type I error probability associated with this test of the null hypothesis is 0.05.

Rz: We are planning a study of a continuous response variable from independent control and experimental subjects with 1 control(s) per experimental subject. In a previous study, the response within each subject group was normally distributed with standard deviation 0.71. If the true difference in the experimental and control means is 2.25 μm , we will need to study 3 experimental subjects and 3 control subjects to be able to reject the null hypothesis that the population means of the experimental and control groups are equal with probability (power) 0.8. The Type I error probability associated with this test of this null hypothesis is 0.05.

2.3 Ethical approval

Ethical approval was not required as per the Dublin Dental University Hospital Research Ethics Committee guidelines.

2.4 Study Design

This was an *in vitro* study involving three different implant types placed in a phantom head and a tabletop model.

2.4.1 Implant type used

A total of 42 dental implants were utilised and analysed in this study. Three different types of implants were used in the investigation, each representing a different design;

1. 14 Straumann® Tissue Level Tapered Effect Implant SLA $\varnothing$ 4.1x12mm RN (Institute Straumann® AG, Basel, Switzerland) which were composed of grade IV commercially pure titanium and had a reverse buttress thread design. The implants were tissue-level and had a divergent smooth tissue collar measuring 2.8mm in length.
2. 14 Ankylos® Bone Level Implants $\varnothing$ 3.5 x 14mm (Dentsply Sirona, Hanau, Germany) which were bone-level with a progressive square thread design. The implants were fabricated from grade II commercially pure titanium.
3. 14 Sweden & Martina® PRAMA FR ZIRTI $\varnothing$ 3.8x13mm (Sweden & Martina® SpA, Padua, Italy) were made from grade IV commercially pure titanium with a convergent anodised micro-grooved tissue collar measuring 2.8mm in length. The threads of the implant were V-shaped.

2.4.2 Preparation of tabletop models

The control group of the dental implants were housed in a polystyrene coping (SIGMA-ALDRICH Scienceware® C3858-50EA). This coping was adjusted with the incorporation of a notch to provide mechanical retention of Triad® material. Triad® acrylic was placed in the coping, and Dentsply® conical reamers were used to prepare the unset Triad®. The Triad® material within the coping was then cured as per manufacturer recommendations. The implants were then checked to confirm that 5mm of the rough surface would remain exposed with a periodontal probe. The implants were then placed in Impregum™ Penta™ Polyether impression material (3M™), and it was allowed to set as per manufacturer recommendations. The implants were then checked to confirm that 5mm of the rough surface had remained exposed. The implants were then mounted on the tabletop with a vice.

A total of 21 implants were placed in the control tabletop group, comprising seven Straumann® Tissue Level Tapered Effect Implants (SLA, $\varnothing$ 4.1 × 12 mm, RN), seven

Ankylos® Bone Level Implants ($\varnothing$ 3.5 × 14 mm), and seven Sweden & Martina® PRAMA FR ZIRTI Implants ($\varnothing$ 3.8 × 13 mm).

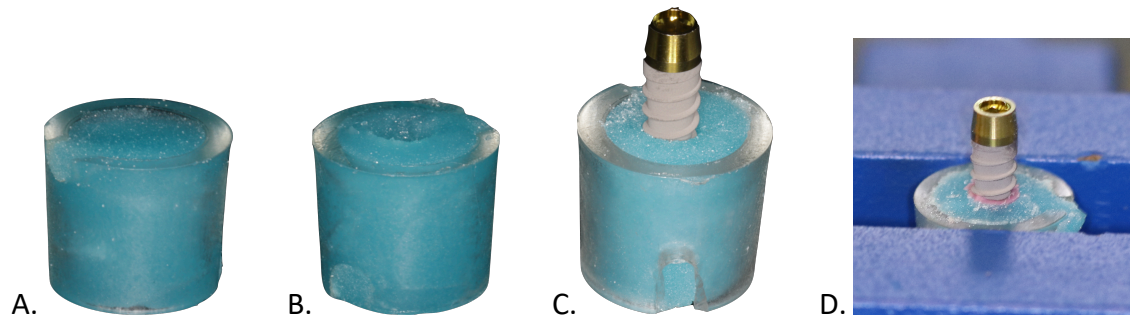


Figure 4: A. Polystyrene coping (SIGMA-ALDRICH Scienceware® C3858-50EA) with Triad® material placement, B. Site preparation in Triad® after use of Dentsply® conical reamers, C. Placement of Sweden & Martina® implant to confirm size of preparation, D. Placement of Sweden & Martina® implant in Impregum™ Penta™ Polyether impression material (3M™).

2.4.3 Preparation of stone casts

In the test group using phantom heads, implants were positioned in the 36 sites within dental stone casts. These stone casts had previously been used in another study (Moorthy *et al.*, 2022). The casts had a magnetic base, which allowed them to be mounted in phantom heads. The pre-existing implant in the 36 site was removed, and a space was prepared within the cast to house the new implant. A customised positioning jig made from Triad® was used to ensure the correct position of the dental implant in the 36 area (Figure 1).



Figure 5: Photographs showing a customised Triad® jig on a cast with an opening over 36 area in A. frontal view, B. lateral view and C. occlusal view.

Similarly to the control group, Dentsply® conical reamers were used to prepare the unset Triad® material, which was then cured as per the manufacturer's recommendations. The implants were then checked to confirm that 5mm of the rough surface would remain exposed after the placement of the impression material. Impregum™ Penta™ Polyether impression material (3M™) was then placed into the space created, and the implants were inserted into the stone casts.

A total of 21 implants were placed in the test phantom head group, comprising seven Straumann® Tissue Level Tapered Effect Implants (SLA, $\varnothing$ 4.1 × 12 mm, RN), seven Ankylos® Bone Level Implants ($\varnothing$ 3.5 × 14 mm), and seven Sweden & Martina® PRAMA FR ZIRTI Implants ($\varnothing$ 3.8 × 13 mm).

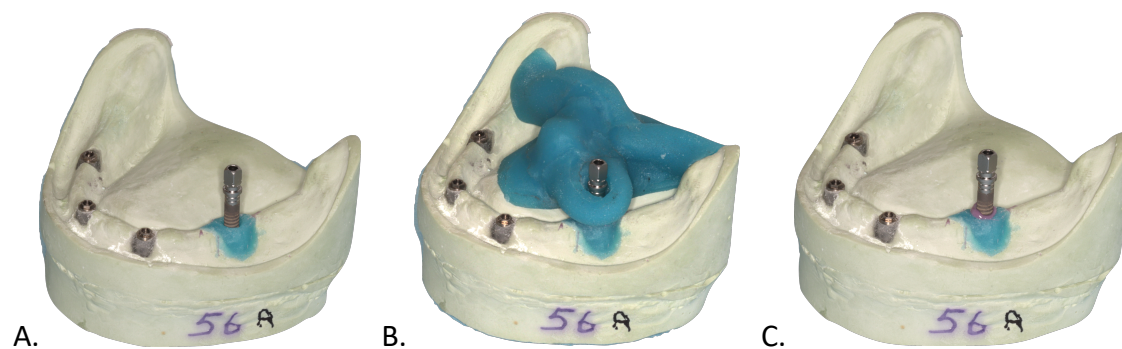


Figure 6: Photographs showing placement of an Ankylos® implant in the 36 site using the customised Triad® jig on cast model, A. Implant in situ in cured Triad on the cast, B. confirmation of location using customised jig and C. placement of Impregum™ Penta™ Polyether impression material (3M™).

2.4.4 IP procedure

One researcher (ED) completed the IP procedures freehand on all implants. IP was performed under x3 magnification using Orascopic™ EyeZoom™ loupes with light illumination in the tabletop and phantom head settings. IP of the different implant types and settings was performed in alternating sequences following a flow chart (Appendix 1).

The following tungsten carbide burs were used to perform IP on the implants; HM379 (023) and HM379U (023) (Hager & Meisinger GmbH) at 40,000 rpm on a 999LT/200 handpiece (W&H Dentalwerk Bürmoos GmbH) with irrigation. The implants were then subsequently polished with a red rubber polisher 9503CA (Sweden & Martina SpA,

Padua, Italy) followed by a green rubber polisher 9533CA (Sweden & Martina SpA, Padua, Italy) at 1500rpm on a 956LT handpiece (W&H Dentalwerk Bürmoos GmbH).

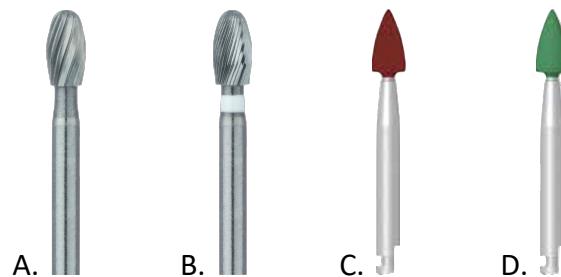


Figure 7: Photos of the burs used as part of the IP protocol, A. Meisinger, Tungsten Carbide HM379 023 XXLFG, B. Meisinger, Tungsten Carbide HM379U 023 XXLFG, C. Sweden & Martina, Red rubber polisher 9503CA, D. Sweden & Martina, Green rubber polisher 9533CA.

A mark was made with a DEHP Bur Diamond FG 109-010 M bur on the internal wall of the implants. In the tabletop (control) group, this mark was placed in an arbitrary location, while in the phantom head (test) group, it was made on the buccal aspect to identify it for analysis purposes. The total amount of time required for IP of each implant was measured using a Garmin® Venu® 2 Plus (Garmin International Inc., Olathe, USA).

IP on the tabletop model was performed freehand in the aforementioned plastic housing, which was rigidly fixated to a tabletop workbench using a vice grip.



Figure 8: Photographs showing the placement of an implant pre-IP in a tabletop vice grip, B. Sweden & Martina® implant after IP and C. Presence of a notch on the internal surface of the tabletop implant

In the phantom head model, IP was performed on the implants on the stone models mounted in the phantom head.

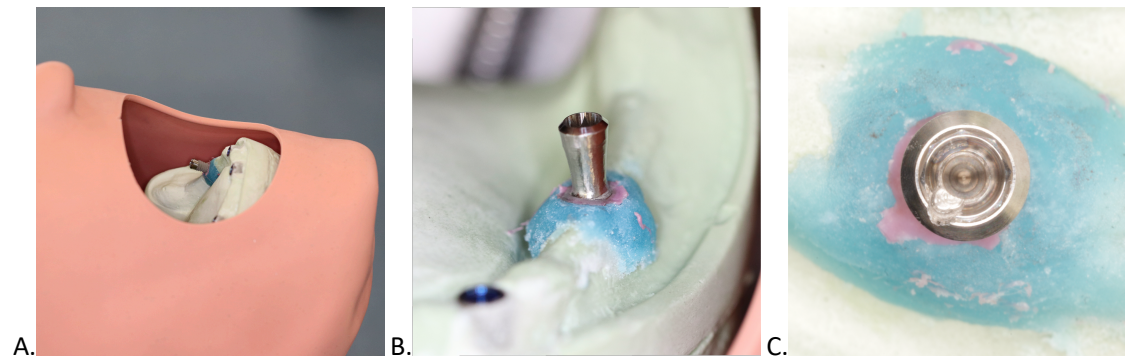


Figure 9: Photographs showing placement of the cast with a Straumann® implant in the 3-6 position in the phantom head model, B. The phantom head implant after IP and C. Presence of a notch on the internal surface demarcating the buccal surface.

2.4.5 Implant removal

After IP, the implants were removed with Crown & Bridge Remover GC KY-Pliers. The remaining impression material on the implant surface was removed by hand and high-pressure air.

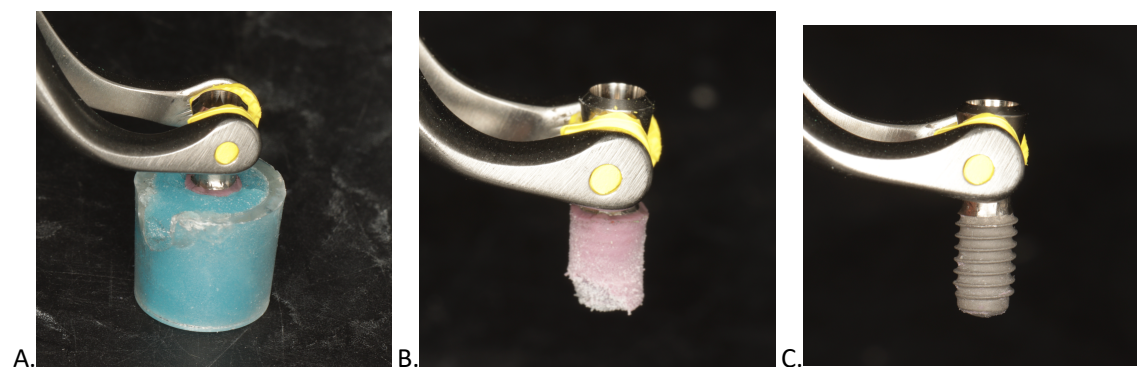


Figure 10: A. Photograph of removal of implant with application of Crown & Bridge Remover GC KY-Pliers, B. The implant after removal with residual Impregum™ Penta™ Polyether impression material (3M™) on its surface, C. Implant after removal of residual Impregum™ Penta™ Polyether impression material (3M™) on surface.

2.4.6 Surface profilometry

A 2D roughness profile analysis (Ra and Rz) was conducted using a Surftest Sj-210 contact stylus profilometer (Mitutoyo Europe GmbH, Neuss, Germany) with a 2µm diameter stylus tip.

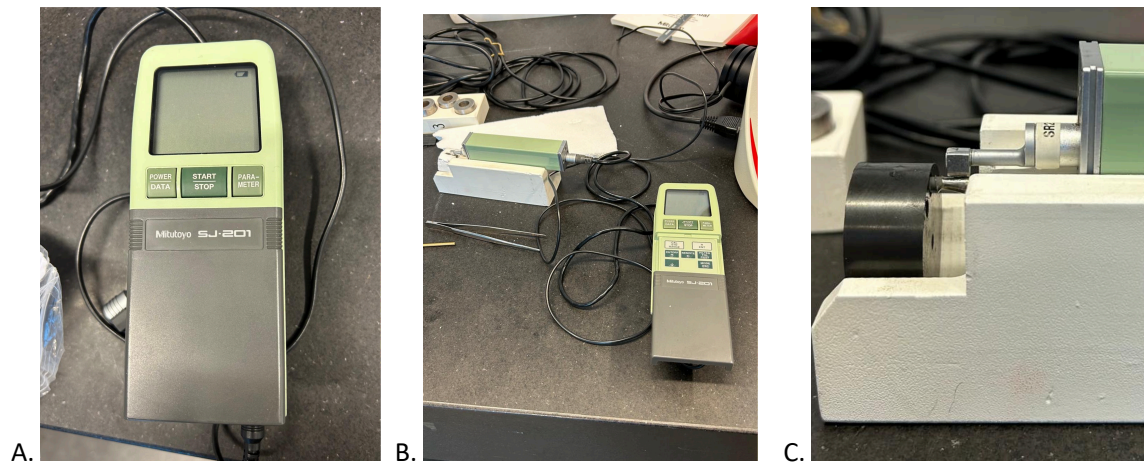


Figure 11: Photos of Surftest Sj-210 contact stylus profilometer (Mitutoyo Europe GmbH, Neuss, Germany).

For the tabletop implants, two opposing sites were randomly selected on each implant. At each site, four surface measurements were obtained, and the mean value was calculated. These measurements from these control implants served as comparators with the test group.

In the phantom head model, two sites on the buccal surface of the implants, indicated by the notch on the internal connection, were measured and identified based on internal surface markings. In addition, two sites on the lingual surface of each implant were also measured. At each site, four surface roughness measurements were taken, and the mean value for each surface (buccal and lingual) was calculated for analysis.

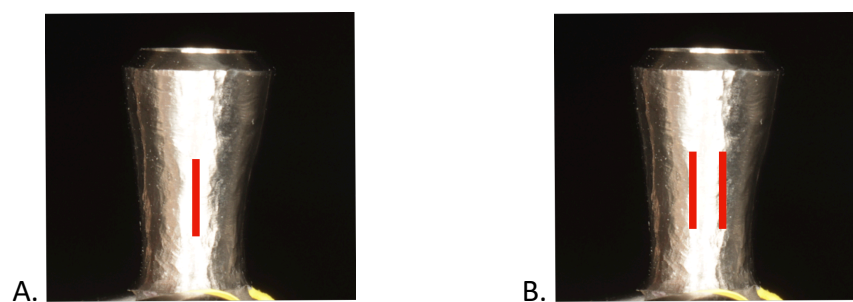


Figure 12: Diagrammatic representation of surface measurement in A. tabletop model, and B. phantom head model.

2.4.7 Scanning electron microscopy (SEM)

Eight implants in total (numbered 1, 5, 8, 9, 10, 13, 35, and 42) were selected for analysis using SEM due to their outlier values in either Ra or Rz surface roughness measurements.

Before the use of SEM, the implants were cleaned with ethanol, rinsed with deionised water, and left to dry in a clean environment. The eight implants selected were individually mounted on aluminium pin stabs (12.5mm dia, 3.2 x 8mm) (Agar Scientific, Rotherham, UK) using conductive carbon adhesive tabs. Conducting Carbon Cement (Leit-C) (Plano GmbH, Wetzlar, Hessen, Germany) was also used around the tip of the implants to secure the specimens better. A Carl Zeiss EVO LS10 (Zeiss, Oberkochen, Germany) was used to obtain images of the samples at two different magnifications (x50 and x100).

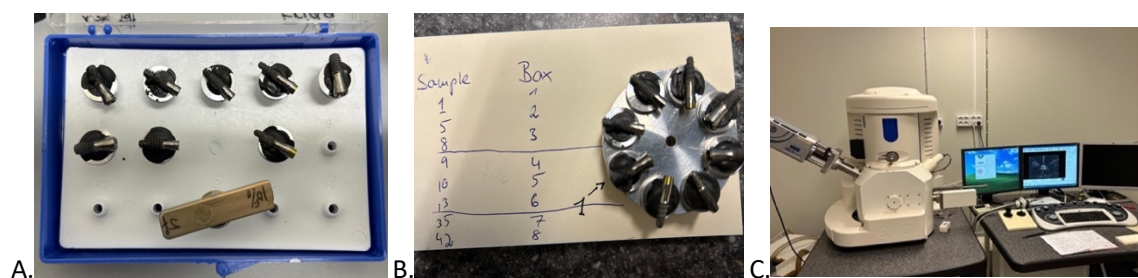


Figure 13: A. Preparation and mounting of implants on aluminium pin stabs (Agar Scientific, Rotherham, UK) using conductive carbon adhesive tabs, B. Labelling of implant before the use of SEM, C. Photo of the Carl Zeiss EVO LS10 (Zeiss, Oberkochen, Germany).

2.4.8 Mass measurement

The mass of the implants was measured before and after IP was performed using a micro-weighing precision scale (Brifit Digital miniscale (Shenzhen Amier Technology) (Guangdong, China)).

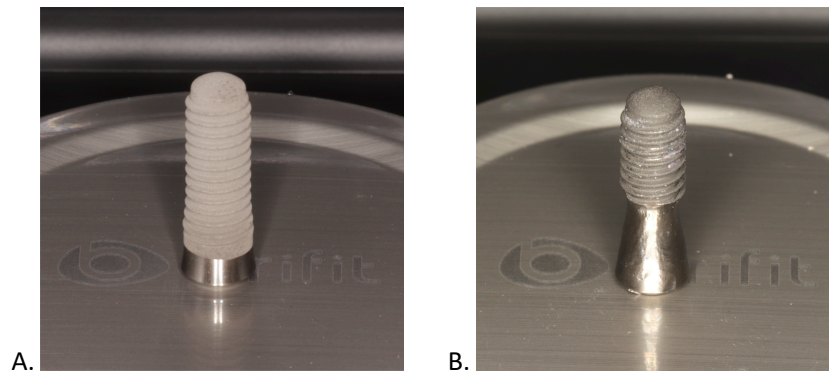


Figure 14: A. Measurement of the mass of a Straumann® implant pre-IP, B. Measurement of the mass of a Straumann® implant post-IP.

2.4.9 Diameter measurement

In addition, the diameter of each implant was recorded 2mm apical to the initial most coronal roughened aspect before and after IP using an electronic calliper (Digital ABS AOS Calliper, Mitutoyo, Sakado, Japan)

2.5 Statistical Analysis

Data was recorded in a data collection sheet in Microsoft® Excel® software. This data was formatted and input to SPSS (Version 29.0.2.0 (20)). All statistical analyses were performed using SPSS (Version 29.0.2.0 (20)) with significance set at $p < 0.05$.

In the tabletop group, two sites were measured, and at each site, four surface roughness readings (Ra and Rz) were recorded. The mean of these measurements was then calculated for each surface, resulting in one Ra and one Rz value per surface per tabletop implant.

In the phantom head group, two sites were measured on both the buccal and lingual surfaces of each implant. At each site, four readings were taken, and the mean was calculated for each site. These means were then averaged across the buccal and lingual sites, resulting in a single Ra and Rz value per surface per implant.

2.5.1 Comparison between tabletop and phantom heads models

Descriptive statistics were used to express surface roughness (Ra and Rz) before and after IP, operative time, implant width, and implant mass between the tabletop (control) and phantom head (test) models. A Shapiro-Wilk test was used to check for normality of data. Median values were compared for each of the parameters using a Mann-Whitney U Test to determine statistical significance.

2.5.2 Comparison among implant types

Descriptive statistics were used to express surface roughness (Ra and Rz), operative time, along with the change in implant width and mass of the tabletop (control) and phantom head (test) models. A Shapiro-Wilk test was used to determine if the data were normally distributed for the different implant types in the two different settings. A two-way ANOVA was used to determine the interaction between implant type and setting on key outcome variables, including differences in surface roughness, procedural time, and material loss (width and mass loss). Post-hoc analysis was conducted with Tukey HSD for pairwise comparisons of implant types. Two-sided independent samples t-tests were performed to compare the means of the Ra, Rz, width difference and mass

difference between the models for each individual implant type, with significant differences reported.

2.5.3 Surface roughness of buccal and lingual implant surfaces in phantom head model

A Shapiro-Wilk test was used to assess the normality of the data for Ra and Rz values on the buccal and lingual surfaces in the phantom head model. Wilcoxon signed rank tests were performed to determine if a significant difference was present between the buccal and lingual surfaces for Ra and Rz.

Descriptive statistics were used to express surface roughness (Ra and Rz) of the buccal and lingual aspects of the implant types in the phantom head. A Shapiro-Wilk test was conducted to assess the normality of the data for Ra and Rz. Paired comparisons of surface roughness (Ra and Rz) between buccal and lingual aspects were performed for each implant type using paired samples *t*-tests or Wilcoxon Signed Rank Tests, depending on data normality. In addition, Cohen's *d* was used on the parametric data to determine the effect size.

2.6 Funding

Funding for all materials was through the postgraduate research budget of the Dublin Dental University Hospital.

3 Results

3.1 Comparison between tabletop and phantom heads models

3.1.1 Descriptive statistics

A total of 42 implants were used in the study, with 21 implants in the tabletop and 21 implants in the phantom head setting.

A Shapiro-Wilk test was used to evaluate the normality of all data produced in the tabletop and phantom head groups. The mean and median values of surface roughness (Ra/ Rz), procedure time, implant mass (pre- and post-operatively), and implant width (pre- and post-operatively) for all implants included in the study are presented in Table 1, while Table 2 presents the median values (IQR).

	Tabletop Mean $\pm$ SD (n = 21)	Phantom Head Mean $\pm$ SD (n = 21)
Ra (μm)	0.43 $\pm$ 0.09	0.53 $\pm$ 0.12
Rz (μm)	2.37 $\pm$ 0.48	2.78 $\pm$ 0.63
Time (sec)	695.48 $\pm$ 55.28	768.43 $\pm$ 59.63
Mass Before (g)	0.48 $\pm$ 0.11	0.48 $\pm$ 0.11
Mass After (g)	0.44 $\pm$ 0.10	0.44 $\pm$ 0.11
Width Before (mm)	3.89 $\pm$ 0.38	3.91 $\pm$ 0.39
Width After (mm)	3.10 $\pm$ 0.18	3.13 $\pm$ 0.22

Table 1: Display of mean and standard deviation (SD) values for Ra, Rz, time, mass before and after IP, along with width before and after IP of all implants in the tabletop and phantom head settings. Bold figures indicate normally distributed parameters from the Shapiro-Wilk test ($p > 0.05$).

	Tabletop Median (IQR)	Phantom Head Median (IQR)
Ra (μm)	0.44 (0.37 – 0.62)	0.53 (0.49 – 0.58)
Rz (μm)	2.47 (1.98 – 2.75)	2.78 (2.56 – 3.01)
Time (s)	685 (648 – 738)	765 (733 – 800.50)
Mass Before (g)	0.43 (0.37 – 0.62)	0.44 (0.37 – 0.62)
Mass After (g)	0.40 (0.34 – 0.56)	0.40 (0.57 – 0.34)
Width Before (mm)	3.81 (3.50 – 4.37)	3.81 (3.51 – 4.39)
Width After (mm)	3.00 (2.97 – 3.26)	3.12 (2.92 – 2.35)

Table 2: Display of median and interquartile ranges (IQR) for Ra, Rz, time, mass before and after IP, along with width before and after IP of all implants in the tabletop and phantom head settings. Bold figures indicate normally distributed parameters from the Shapiro-Wilk test ($p > 0.05$).

3.1.2 Inferential statistics

Mann-Whitney U Tests were conducted to determine whether statistically significant differences existed between the tabletop (control) model and the phantom head (test) model.

3.1.2.1 Average surface roughness Ra

A statistically significant difference was found between the Ra values of the implant prepared in standardised conditions (Ra: 0.44 [0.37 – 0.62]) and compared to the ones prepared in a simulated clinical environment (Ra: 0.53 [0.49 – 0.58])($p = 0.004$). This indicates access has a significant effect on the effectiveness of implant preparation during IP.

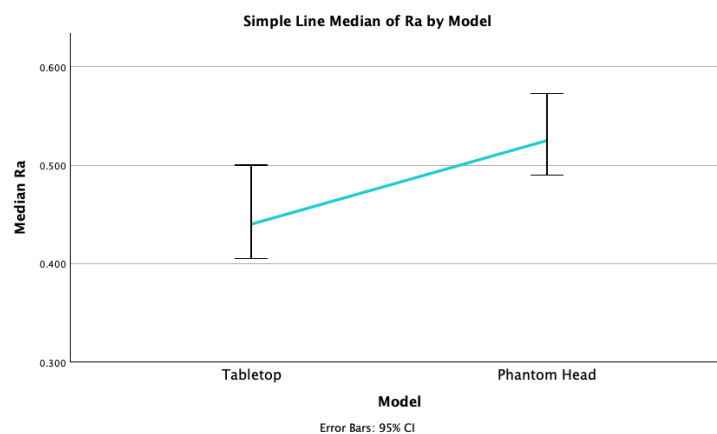


Figure 15: Graphical representation of the difference between the Ra values of implants prepared on a tabletop and those prepared in a phantom head

3.1.2.2 Surface roughness Rz

A statistically significant difference was found between the Rz values of the implant prepared in standardised conditions (Rz: 2.47 [1.98 – 2.75] compared to the ones prepared in a simulated clinical environment (Rz: 2.78 [2.56 – 3.01]) ($p = 0.019$). This indicates access has a significant effect on the effectiveness of implant preparation during IP.

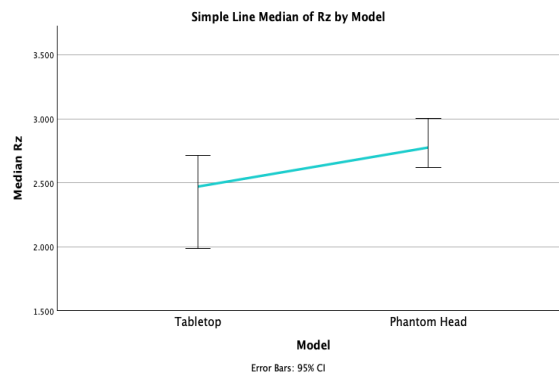


Figure 16: Graphical representation of the difference between the Rz values of implants prepared on a table top and those prepared in a phantom head

3.1.2.3 Time

A statistically significant difference was found between the time required for implants prepared in standardised conditions (685 sec [648 – 738]) compared to the ones prepared in a simulated clinical environment (765 sec [733 – 800.50]) ($p < 0.001$). This indicates access has a significant effect on the amount of time required for implant preparation during IP.

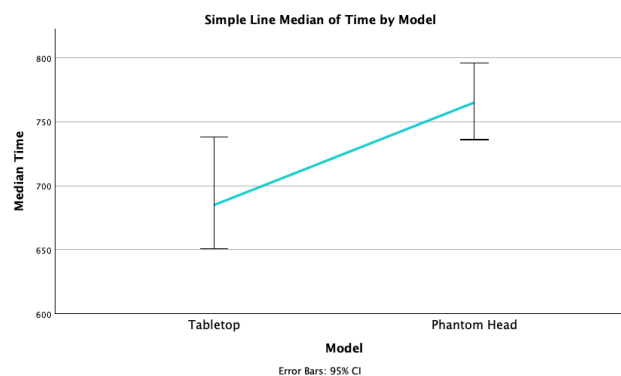


Figure 17: Graphical comparison of the time needed for implant preparation on a tabletop versus in a phantom head model.

3.1.2.4 Implant Mass

No statistically significant differences were found in implant mass between the implants prepared in a standardised tabletop setting compared to those in a simulated clinical environment, either before ($p = 0.623$) or after IP ($p = 0.725$), as measured with an electronic scale. This indicates that access does not have a significant effect on the amount of implant mass removed during IP.

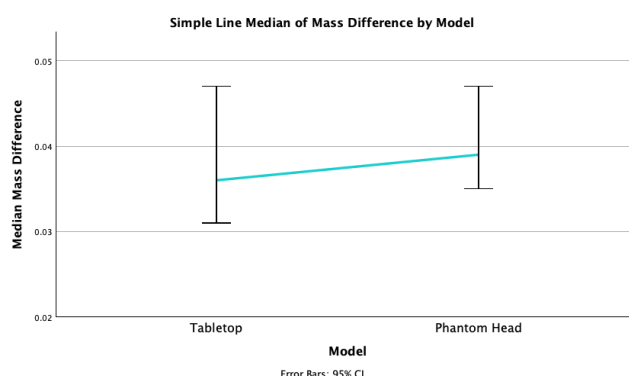


Figure 18: Graphical representation of the difference in mass between implants prepared on a tabletop and those prepared in a phantom head.

3.1.2.5 Width of implants

No statistically significant differences were found in implant widths between the implants prepared in a standardised tabletop setting compared to those in a simulated clinical environment, either before ($p = 0.367$) or after IP ($p = 0.821$), as measured with an electronic calliper. This indicates that access does not have a significant effect on the width reduction of implants during IP.

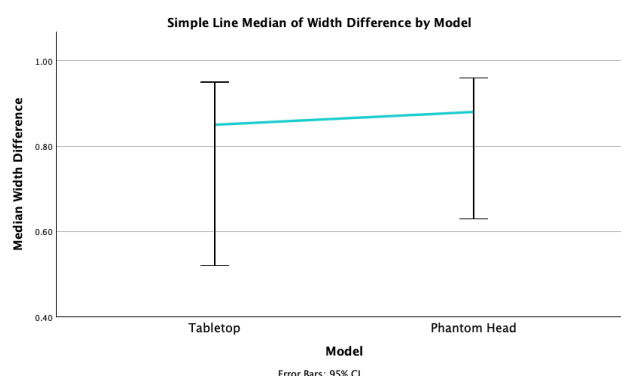


Figure 19: Graphical representation of the difference in width between implants prepared on a table top and those prepared in a phantom head

3.2 Comparison among implant systems

3.2.1 Descriptive statistics

The normality of the distribution of the values generated was tested using the Shapiro-Wilk test. The mean and standard deviation (SD) values, along with medians and interquartile ranges (IQR), are presented in Tables 3, 4 and 5 for the differing implant types and settings.

Straumann® (n=14)	Tabletop	Phantom Head	Tabletop	Phantom Head
	Mean, SD	Mean, SD	Median (IQR)	Median (IQR)
Ra (µm)	0.45 ± 0.09	0.56 ± 0.06	0.45 (0.41 – 0.51)	0.53 (0.51 – 0.57)
Rz (µm)	2.60 ± 0.40	2.94 ± 0.45	2.69 (2.16 – 2.80)	2.81 (2.77 – 3.00)
Time (s)	713.29 ± 69.58	791.43 ± 53.47	738 (651 – 750)	786 (736 – 855)
Width Difference (mm)	1.07 ± 0.13	1.01 ± 0.08	1.07 (0.95 – 1.24)	0.98 (0.96 – 1.06)
Mass difference (g)	0.05 ± 0.01	0.05 ± 0.01	0.05 (0.04 – 0.07)	0.45 (0.43 – 0.51)

Table 3: Display of mean and standard deviation (SD) values, along with medians and interquartile ranges (IQR) for Straumann® implants for Ra, Rz, time, width difference and mass difference for implants prepared in tabletop and phantom head settings. Bold figures indicate normally distributed parameters from the Shapiro-Wilk test ($p > 0.05$).

Ankylos® (n=14)	Tabletop	Phantom Head	Tabletop	Phantom Head
	Mean, SD	Mean, SD	Median (IQR)	Median (IQR)
Ra (µm)	0.42 ± 0.12	0.57 ± 0.17	0.42 (0.33 – 0.55)	0.53 (0.49 – 0.62)
Rz (µm)	2.10 ± 0.54	2.94 ± 0.94	1.98 (1.59 – 2.72)	2.86 (2.50 – 3.02)
Time (s)	701.29 ± 50.10	788.43 ± 45.96	685 (670 – 719)	788.00 (750 – 835)
Width Difference (mm)	0.45 ± 0.08	0.51 ± 0.14	0.46 (0.38 – 0.52)	0.48 (0.38 – 0.66)
Mass difference (g)	0.03 ± 0.01	0.04 ± 0.01	0.03 (.02 – .03)	0.04 (0.03 – 0.05)

Table 4: Display of mean and standard deviation (SD) values, along with medians and interquartile ranges (IQR) for Ankylos® implants for Ra, Rz, time, width difference and mass difference for implants prepared in tabletop and phantom head settings. Bold figures indicate normally distributed parameters from the Shapiro-Wilk test ($p > 0.05$).

Sweden & Martina® (n=14)	Tabletop	Phantom Head	Tabletop	Phantom Head
	Mean, SD	Mean, SD	Median (IQR)	Median (IQR)
Ra (µm)	0.43 ± .06	0.49 ± .11	0.44 (0.42 – 0.47)	0.50 (0.39 – 0.61)
Rz (µm)	2.41 ± 0.41	2.55 ± 0.57	2.47 (2.17 – 2.78)	2.63 (2.01 – 3.12)
Time (s)	671.86 ± 42.13	725.43 ± 60.318	674 (645 – 700)	729 (690 – 770)
Width Difference(mm)	0.85 ± 0.034	0.81 ± 0.12	0.85 (0.82 – 0.87)	0.88 (0.70 – 0.91)
Mass difference (g)	0.037 ± 0.006	0.036 ± 0.008	0.035 (0.031 – 0.041)	0.037 (0.03 – 0.039)

Table 5: Display of mean and standard deviation (SD) values, along with medians and interquartile ranges (IQR) for Sweden & Martina® implants for Ra, Rz, time, width difference and mass difference for implants prepared in tabletop and phantom head settings. Bold figures indicate normally distributed parameters from the Shapiro-Wilk test ($p > 0.05$).

3.2.2 Inferential statistics

A two-way analysis of variance (ANOVA) was used to assess the influence of implant type and the setting in which IP was performed, with it being in either a tabletop or a phantom head. Post-hoc comparisons were performed with Tukey's HSD testing.

3.2.2.1 Surface roughness Ra

Average surface roughness Ra was measured after completing IP, and the Ra values of different implant types and the settings in which IP was performed were compared. An ANOVA test did not find a significant difference among the three implant types ($p = 0.620$). However, the average surface roughness Ra between the phantom model and tabletop setting did reach statistical significance ($p = 0.006$). The interaction effect was not statistically significant ($p = 0.467$).

A two-sided independent sample t-test revealed a significant difference for Ra of $-0.084 \mu\text{m}$ (95% CI: -0.168 to -0.001) was present for the Straumann® implant in the tabletop and phantom head model ($p = 0.048$). The difference for the Ankylos® implant approached the level of statistical significance ($p = 0.076$).

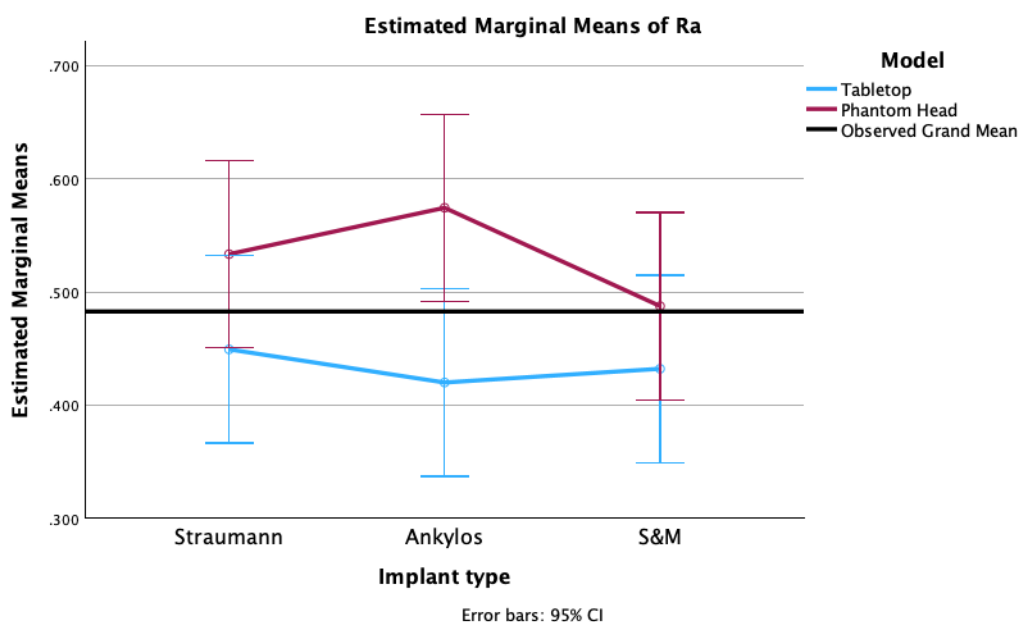


Figure 20: Graphical representation of the Ra values of implant types prepared in a tabletop and phantom head model.

3.2.2.2 Surface roughness Rz

Surface roughness Rz was measured after IP, and the Rz of the different implant types and of the setting in which the IP was performed were compared. An ANOVA test did not find a significant difference in Rz values among the three implant types ($p = 0.473$). However, a significant difference in average surface roughness Rz between the phantom model and tabletop model of the IP did reach statistical significance ($p = 0.023$). The interaction effect was not statistically significant ($p = 0.216$).

A two-sided independent sample t-test revealed that the difference of Rz between the Ankylos® implants in the phantom head and tabletop models approached statistical significance ($p = 0.064$).

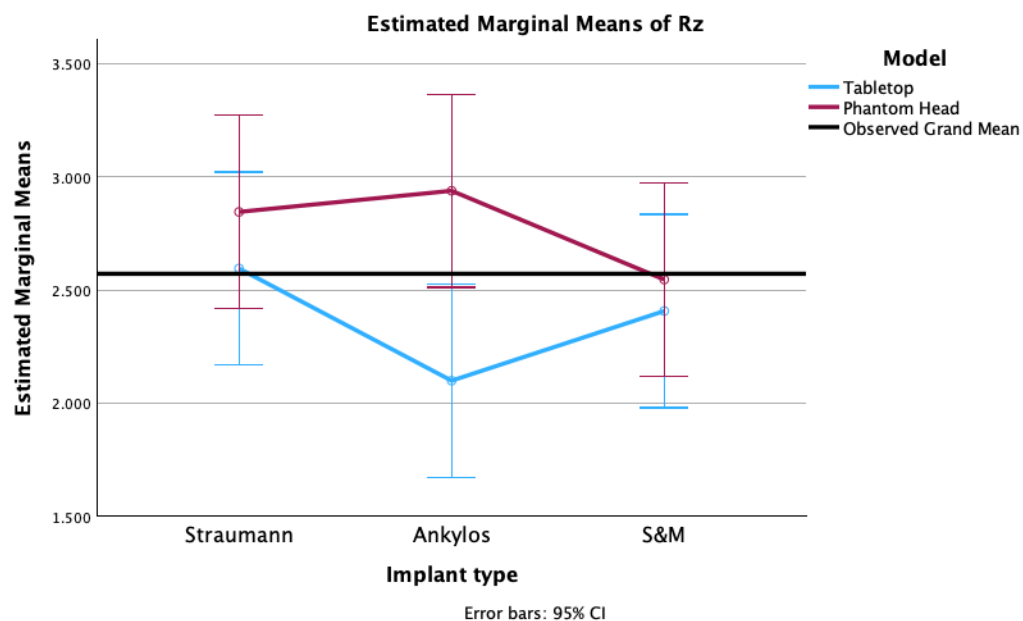


Figure 21: Graphical representation of the Rz values of implant types prepared in a tabletop and phantom head model.

3.2.2.3 Time

The time required to perform IP was recorded during the procedure. An ANOVA test revealed a statistically significant difference in operative time required between the two different settings ($p < 0.001$), along with a statistically significant difference between implant type ($p = 0.027$).

A Tukey HSD post hoc test found significant differences in time required among the implant types, with Straumann® implants requiring significantly more time, 53.71 seconds, for IP compared to Sweden and Martina implants (95% CI; 3.49, 103.94)($p = 0.034$). Additionally, Sweden and Martina implants took 46.21 seconds less time to prepare compared to Ankylos® implants (95% CI; -96.44, 4.01)($p = 0.034$). There was no statistically significant difference in operative time required between Straumann® implants compared to Ankylos® implants, with a difference of 7.50 seconds (95% CI; -42.73, 57.73)($p = 0.929$). The interaction effect was not statistically significant ($p = 0.702$).

A two-sided independent sample t test revealed a significant difference for time taken between Straumann® implants on the tabletop and the phantom head setting of -78.14 seconds (95% CI; -155.41 to -5.877)($p = 0.036$). In addition, a significant difference of -87.14 seconds was also found for Ankylos® implants (95% CI; -143.13 to -31.15)($p = 0.005$).

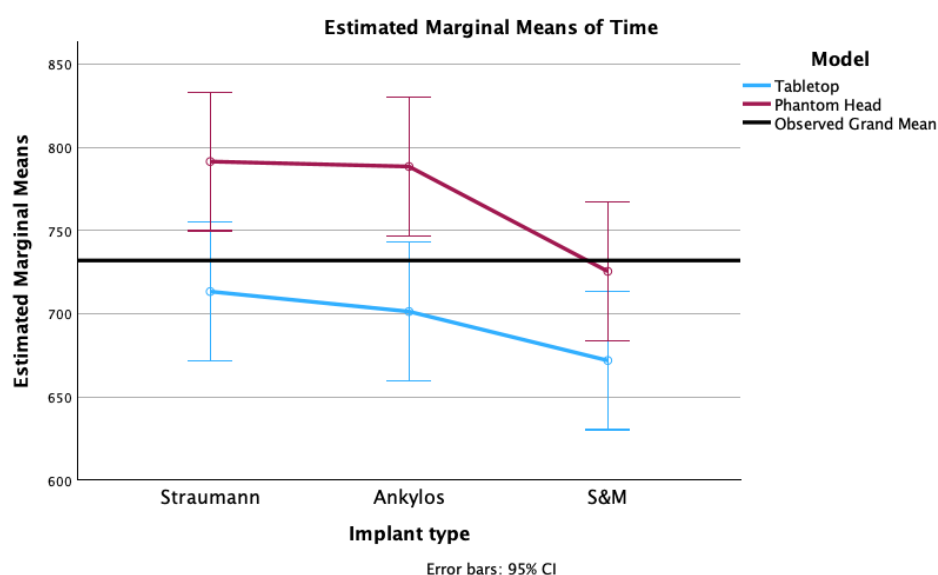


Figure 22: Graphical representation of the time required for IP of the different implant types prepared in a tabletop and phantom head model.

3.2.2.4 Implant width

Following the IP procedures, the width of the implants was measured at the previously specified sites, and these values were compared to the measurements taken before IP. An ANOVA test revealed a statistically significant difference in the reduction of implant width among the three implant types ($p < 0.001$). However, the setting in which the IP was performed did not have a significant impact on the change in implant width ($p = 0.721$).

A Tukey HSD post hoc analysis revealed that Straumann® implants exhibited the greatest mean width change following IP, significantly exceeding both Ankylos® (0.5621mm, 95% CI [0.4670, 0.6572], $p < 0.001$) and Sweden & Martina® implants (0.2086mm, 95% CI [0.1135, 0.3037], $p < 0.001$). Ankylos® implants demonstrated the smallest reduction in width, which was significantly lower than Sweden & Martina® (-0.3536mm, 95% CI [-0.4487, -0.2585], $p < 0.001$). The interaction effect was not statistically significant ($p = 0.233$). Two-sided independent sample t-tests comparing the individual implant types in the two settings for width difference were not statistically significant ($p > 0.05$).

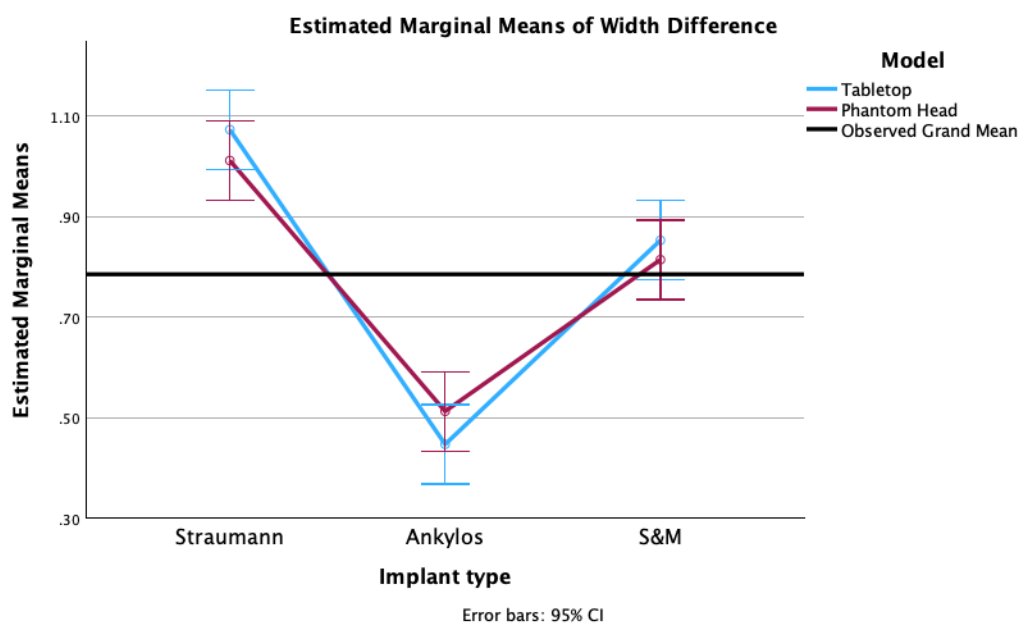


Figure 23: Graphical representation of the difference in width after IP of the different implant types prepared in a tabletop and phantom head model.

3.2.2.5 Implant mass

After IP was performed on the implant, the mass of the implants was measured, and these values were compared to the measurements taken before IP. An ANOVA test revealed a statistically significant difference in the reduction of implant width among the three implant types ($p < 0.001$). However, the setting in which the IP was performed did not have a significant impact on the change in implant mass ($p = 0.926$).

A Tukey HSD post hoc test found Straumann® implants had a significantly greater mass reduction compared to both Ankylos® (0.0162g, 95% CI [0.0086, 0.0239], $p < .001$) and Sweden & Martina® (0.0134g, 95% CI [0.0058, 0.0211], $p < .001$). No significant difference in mass reduction was found between Ankylos® and Sweden & Martina® dental implants (-0.0028g, 95% CI [-0.0104, 0.0049], $p = .649$). The interaction effect was not statistically significant ($p = 0.06$). Two-sided independent sample t-tests comparing the individual implant types in the two settings for mass loss were not statistically significant ($p > 0.05$).

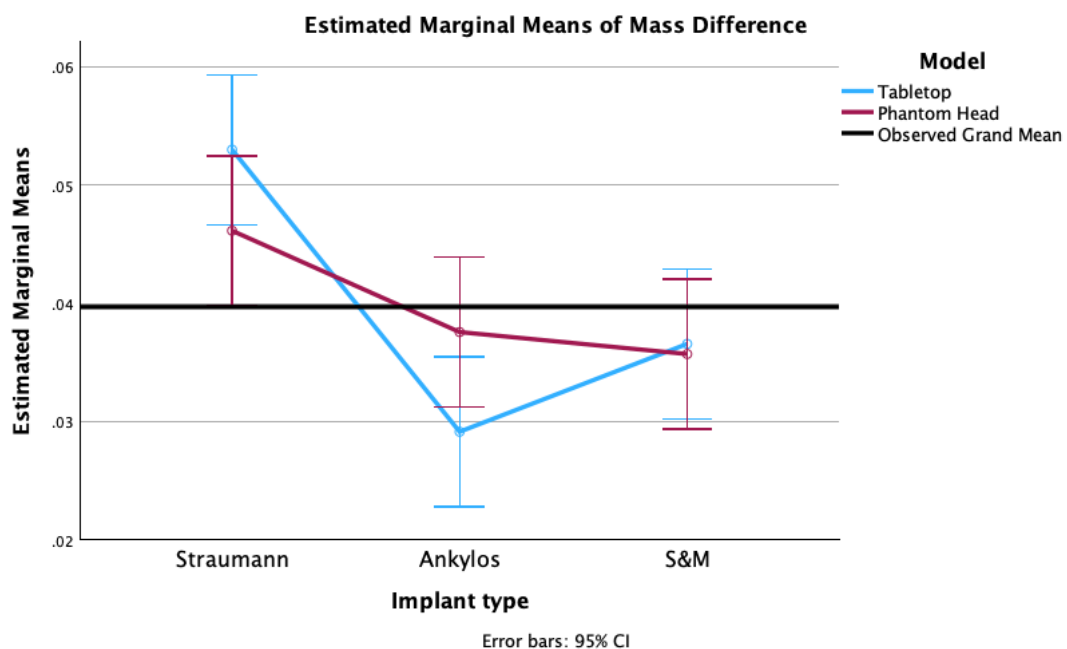


Figure 24: Graphical representation of the difference in mass after IP of the different implant types prepared in a tabletop and phantom head model.

3.3 Surface roughness of buccal and lingual implant surfaces in phantom head model

3.3.1 Descriptive statistics

A Shapiro-Wilk test was used to assess the normality of the data for Ra and Rz on both buccal and lingual surfaces in the phantom head model. Overall, Ra buccal and Rz buccal data were normally distributed ($p > 0.05$), whereas Ra lingual and Rz lingual data were not normally distributed ($p < 0.05$). Wilcoxon signed-rank tests were performed to compare the median values of Ra and Rz for the buccal and lingual surfaces of the implants in the phantom head.

A Shapiro-Wilk test was performed to assess the normality of data for Ra and Rz on the buccal and lingual surfaces of each implant type in the phantom head model. Data was normally distributed for Ra and Rz for Straumann® and Sweden & Martina® implants on both surfaces ($p > 0.05$). Two-sided paired samples t-tests were used to assess the differences between the roughness values of the buccal and lingual on these implants. Ankylos® implants exhibited normally distributed Ra and Rz values on the buccal surface ($p > 0.05$), although data was not normally distributed on the lingual aspect for Ra ($p = 0.011$) and Rz ($p = 0.003$). Therefore, non-parametric testing with the Wilcoxon signed-rank test was conducted on the Ankylos® implants.

Overall	Phantom Head Buccal Mean, SD	Phantom Head Lingual Mean, SD	Phantom Head Buccal Median (IQR)	Phantom Head Lingual Median (IQR)
Ra (μm)	0.51 $\pm$ 0.13	0.55 $\pm$ 0.16	0.52 (0.41 - 0.60)	0.55 (0.46 – 0.63)
Rz (μm)	2.72 $\pm$ 0.70	2.84 $\pm$ 0.87	2.70 (2.20 - 3.36)	2.64 (2.33 - 3.14)

Table 6: Display of mean and standard deviation (SD) values, along with medians and interquartile ranges (IQR) for Ra and Rz for the buccal and lingual aspects of implants overall prepared in the phantom head settings. Bold figures indicate normally distributed parameters from the Shapiro-Wilk test ($p > 0.05$).

Straumann®	Phantom Head Buccal Mean, SD	Phantom Head Lingual Mean, SD	Phantom Head Buccal Median (IQR)	Phantom Head Lingual Median (IQR)
Ra (μm)	0.51 $\pm$ 0.10	0.56 $\pm$ 0.06	0.52 (0.41 - 0.58)	0.57 (0.51 - 0.59)
Rz (μm)	2.75 $\pm$ 0.58	2.94 $\pm$ 0.45	2.90 (2.36 - 3.00)	2.92 (2.62 - 3.28)

Table 7: Display of mean and standard deviation (SD) values, along with medians and interquartile ranges (IQR) for Ra and Rz for the buccal and lingual aspects of Straumann® implants prepared in the phantom head settings. Bold figures indicate normally distributed parameters from the Shapiro-Wilk test ($p > 0.05$).

Ankylos®	Phantom Head Buccal Mean, SD	Phantom Head Lingual Mean, SD	Phantom Head Buccal Median (IQR)	Phantom Head Lingual Median (IQR)
Ra (µm)	0.53 ± 0.16	0.62 ± .22	0.54 (0.42 - 0.70)	0.55 (0.47 - 0.64)
Rz (µm)	2.75 ± 0.85	3.13 ± 1.31	2.70 (2.25 - 3.40)	2.63 (2.30 - 3.19)

Table 8: Display of mean and standard deviation (SD) values, along with medians and interquartile ranges (IQR) for Ra and Rz for the buccal and lingual aspects of Ankylos® implants prepared in the phantom head settings. Bold figures indicate normally distributed parameters from the Shapiro-Wilk test ($p > 0.05$).

Sweden & Martina®	Phantom Head Buccal Mean, SD	Phantom Head Lingual Mean, SD	Phantom Head Buccal Median (IQR)	Phantom Head Lingual Median (IQR)
Ra (µm)	0.50 ± 0.12	0.48 ± 0.14	0.45 (0.38 - 0.63)	0.45 (0.37 - 0.65)
Rz (µm)	2.64 ± 0.75	2.45 ± 0.59	2.47 (1.96 - 3.53)	2.53 (1.89 - 2.94)

Table 9: Display of mean and standard deviation (SD) values, along with medians and interquartile ranges (IQR) for Ra and Rz for the buccal and lingual aspects of Sweden & Martina® implants prepared in the phantom head settings. Bold figures indicate normally distributed parameters from the Shapiro-Wilk test ($p > 0.05$).

3.3.2 Inferential statistics

3.3.2.1 Overall

Wilcoxon signed-rank tests were conducted to assess whether there was a significant difference in surface roughness between the buccal and lingual aspects of implants in the phantom. The results indicated that, for Ra, there was no statistically significant difference between the buccal and lingual surfaces ($p = 0.498$). Furthermore, the outcome of the Wilcoxon Signed Rank Test comparing the Rz showed no significant differences between the buccal and lingual aspects of the implants overall in the phantom head setting ($p = 0.821$).

3.3.2.2 Straumann® implants

For Straumann® implants in the phantom head model, the mean difference between the buccal and lingual surfaces for Ra was not statistically significant at $-0.04821\mu\text{m}$ ($p = 0.430$; 95% CI $[-0.18758, 0.09115]$). The effect size was calculated using Cohen's d , which was -0.320 (95% CI; -1.069 to 0.429).

The Rz value for the buccal implant surface was smoother than the lingual by $-0.188\text{ }\mu\text{m}$, although this was not statistically significant ($p = 0.638$; 95% CI: -1.113 to 0.738). The corresponding effect size, evaluated with Cohen's d , was -0.187 (95% CI: -0.928 to 0.394), which is considered small.

3.3.2.3 Ankylos® implants

Wilcoxon signed-rank tests were performed to determine if the difference in surface roughness between the buccal and lingual aspects of the Ankylos® implants in the phantom was significantly different. The results of this test showed that for Ra there was no statistically significant difference between the buccal and lingual surfaces ($p = 0.237$). Additionally, the outcome of the Wilcoxon Signed Rank Test comparing the Rz revealed no significant differences between the buccal and lingual aspects of these implants in the phantom head setting ($p = 0.398$).

3.3.2.4 Sweden & Martina® implants

For Sweden & Martina® implants, the difference between the mean roughness Ra for the buccal and lingual surfaces was $0.02\text{ }\mu\text{m}$ and did not reach statistical significance ($p = 0.725$; 95% CI $[-0.11, 0.15142]$). Cohen's d was 0.140 , indicating a small difference between the Ra values of the buccal and lingual surfaces, with 95% confidence intervals of -0.611 to 0.879 .

The mean difference of Rz of Sweden & Martina® showed a difference of $0.19714\text{ }\mu\text{m}$ for the Rz on the buccal side compared to the lingual side. However, this difference was not statistically significant between the surfaces ($p = 0.493$; 95% CI $[-0.46433, 0.85862]$). Cohen's d was 0.276 , indicating a positive effect, although this did not reach statistical significance (95% CI: $-0.491, 1.021$).

3.4 Scanning electron microscope images

Implant 1 (Straumann®, Tabletop) had the highest surface roughness among the tabletop group ($R_a = 0.58 \mu\text{m}$, $R_z = 3.19 \mu\text{m}$). The image from the SEM had an uneven surface with scattered protrusions, shallow pits, and residual irregularities. These features are consistent with the elevated roughness values recorded.

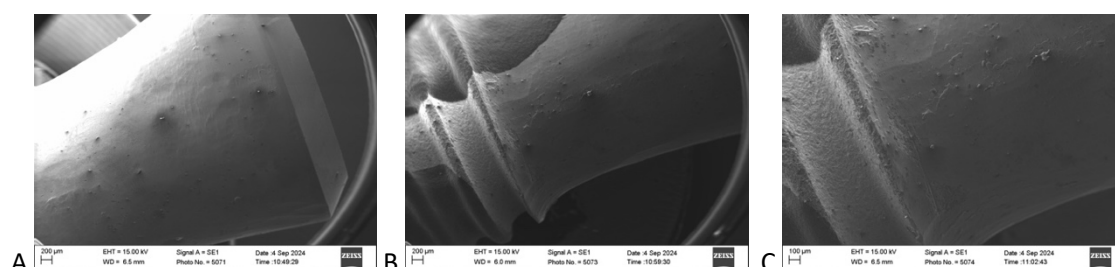


Figure 25: SEM images of Implant 1 A. Coronal area of IP under x50 magnification, B. Apical area of IP under x50 time magnification, C. Apical area of IP under x100 magnification.

Implant 5 (Ankylos®, Lingual surface) showed the highest surface roughness in the phantom head group and throughout the study ($R_a = 1.09 \mu\text{m}$, $R_z = 5.98 \mu\text{m}$). SEM images displayed a coarse and irregular surface, with a prominent ridge in the centre of the treatment implant surface. These features are consistent with the elevated roughness measurements observed.

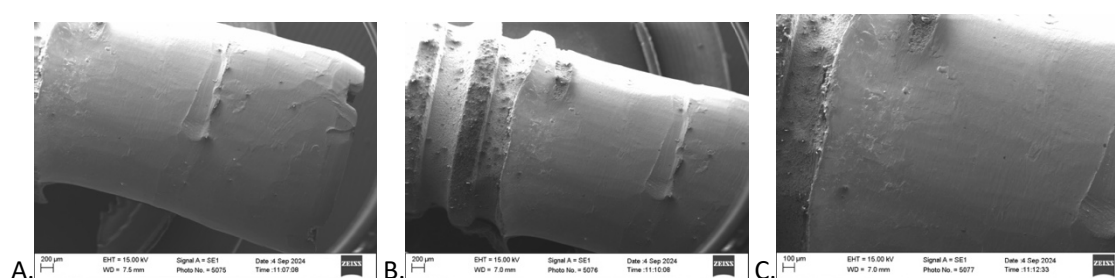


Figure 26: SEM images of Implant 5. A. Coronal area of IP under x50 magnification, B. Apical area of IP under x50 time magnification, C. Apical area of IP under x100 magnification.

Implant 8 (Ankylos®, Tabletop) had the lowest surface roughness values in the study, with a Ra of 0.25 μm and Rz of 1.495 μm . SEM imaging of the implant surface showed a smooth surface with few irregularities.

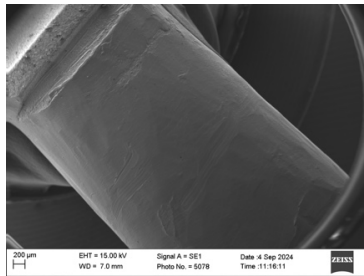


Figure 27: SEM images of Implant 8. Area of IP under x50 magnification.

Implant 9 (Sweden & Martina® Tabletop) had moderate surface roughness values, with Ra at 0.44 μm and Rz at 2.47 μm . SEM analysis showed a surface with a mix of smoother areas and scattered areas of protrusion.

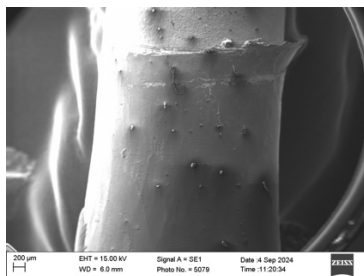


Figure 28: SEM images of Implant 9. Area of IP under x50 magnification.

Implant 10 (Buccal surface, Phantom Head) also showed moderate surface roughness values, with a Ra of 0.4735 μm and a Rz of 2.501 μm . The SEM image reveals a reasonably smooth surface, though it has fine scratches and shallow grooves. These may be the result of the use of the rotary tungsten carbide burs during IP.

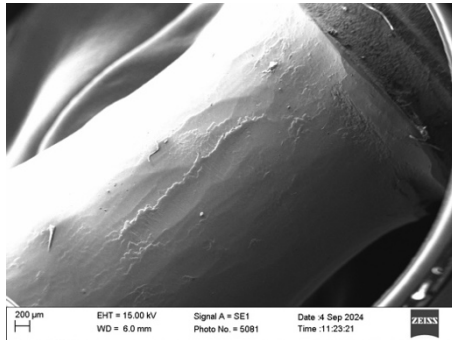


Figure 29: SEM images of Implant 10. Area of IP under x50 magnification.

Implant 13 (Tabletop) had the lowest roughness values for Straumann® implants in the tabletop and phantom head models in the study (Ra = 0.29 μm , Rz = 1.99 μm). SEM imaging showed a uniform reduction and polishing of the implant surface with minimal protrusions and grooves present.

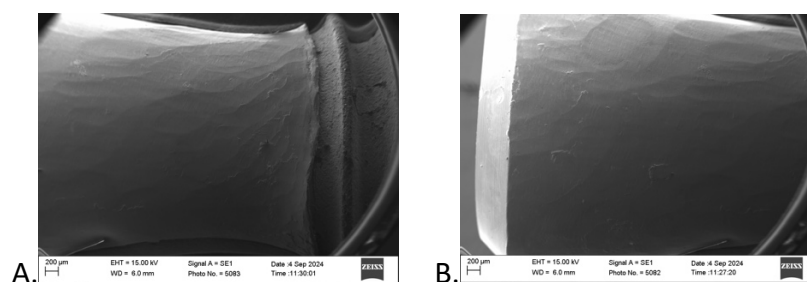


Figure 30: SEM images of Implant 13. A. Apical area of IP under x50 magnification, B. Coronal area of IP under x50 time magnification.

Implant 35 (Buccal surface) showed relatively high surface roughness values for those found in the phantom head model ($R_a = 0.70 \mu\text{m}$, $R_z = 3.4 \mu\text{m}$). SEM images revealed a visibly uneven surface with scattered depressions and irregular polishing marks.

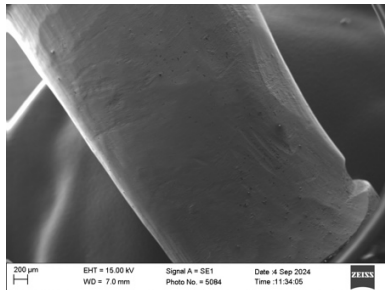


Figure 31: SEM images of Implant 35 area of IP under x50 magnification.

Implant 42 (Sweden & Martina®, Buccal surface, Phantom Head) had low surface roughness values ($R_a = 0.38 \mu\text{m}$, $R_z = 1.81 \mu\text{m}$). SEM images show a smoothed implant surface with fine lines, isolated surface pitting, and protrusions.

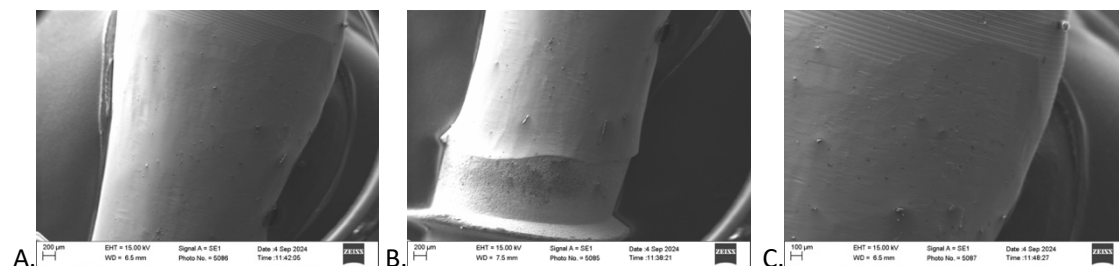


Figure 32: SEM images of Implant A. Coronal area of IP under x50 magnification, B. Apical area of IP under x50 magnification, C. Coronal area of IP under x100 magnification

4 Discussion

This *in vitro* study aimed to evaluate the influence of operator access on IP outcomes, specifically surface roughness parameters (Ra and Rz) and material loss on dental implant surfaces. Two models were used to simulate different clinical scenarios: a table-top model, allowing unrestricted access and representing an idealised setting, and a phantom head model, which imposed limited access to better replicate the clinical situation. The study also examined whether variations in implant type—based on surface characteristics and macro design—affected these outcomes. Finally, for implants prepared in the phantom head model, the surface roughness was compared between the buccal and lingual aspects to assess access-related differences.

The primary aetiological factor for peri-implantitis is the presence of peri-implant plaque biofilm (Herrera *et al.*, 2023). The purpose of IP is bacterial decontamination and a reduction in the macro and micro surface roughness of dental implants, resulting in decreased bacterial adherence and allowing for effective plaque control by the patient and practitioner (Azzola *et al.*, 2020; Schwarz *et al.*, 2022; Bertl *et al.*, 2024). In the existing literature, it has been demonstrated that turned implants have a lower risk of being affected by peri-implantitis compared to those with roughened surfaces, although evidence is not conclusive (Esposito *et al.*, 2014; Stavropoulos *et al.*, 2021). Based on this, implants with peri-implantitis which have undergone IP may be less prone to bacterial plaque accumulation and perpetuation of the inflammatory process driven by bacterial plaque (Azzola *et al.*, 2020; Herrera *et al.*, 2023; Bertl *et al.*, 2024).

IP can allow for the complete decontamination of the implant surface compared to other instrumentation techniques (El Chaar *et al.*, 2020). IP appears to reduce biofilm adhesion and regrowth on treated implant surfaces. In a case report, Geremias *et al.* (2017) applied three different treatment strategies applied to three different peri-implantitis-affected implants within the same patient: IP, open flap debridement combined with citric acid application, and open flap debridement alone. Despite these interventions, all three implants had to be removed after four months due to treatment failure. Interestingly, when the explanted implants were later inoculated with *Streptococcus*

mutans in vitro, those that had undergone IP or citric acid decontamination showed reduced planktonic bacterial growth compared to the implant treated with debridement alone (Geremias et al., 2017).

Surface roughness within the oral cavity plays a critical role to accumulate in biofilm accumulation. The threshold for average surface roughness (Ra) of below 0.2 μm has been associated with increasing bacterial colonisation (Quirynen & Bollen 1995; Quirynen *et al.*, 1996). Azzola *et al.* (2020) conducted an *in-situ* study, in which implants with moderately roughened surfaces or those treated with IP were housed in an intra-oral tray and worn by patients. After five days, IP-treated implants had a reduced surface area covered by bacteria compared to the moderately roughened implants. In addition, the biofilm composition on the IP implants was less mature Azzola *et al.* (2020). Similarly, Bürgers *et al.* (2010) demonstrated that roughened titanium surfaces (Ra; 0.95 μm) housed by intraoral splints worn by six participants had an increased adhesion and surface area coverage of bacteria compared to machined titanium surfaces (Ra; 0.15 μm). However, this study only assessed microbes after 12 hours of appliance wear by the patient.

Previous studies have determined that surface roughness under a “threshold Ra” of 0.2 μm did not significantly impact peri-implant supra- or subgingival plaque composition (Bollen *et al.*, 1996; Quirynen *et al.*, 1996). Elter *et al.* (2008) found that supra-gingival biofilm formation on abutments with an average surface roughness of 0.2 μm had significantly reduced plaque accumulation compared to rougher abutment surfaces. However, there was no significant difference found for subgingival biofilm formation between abutments with varying roughness ($p > 0.05$) (Elter *et al.*, 2008). These differences in the supra- and sub-gingival microbial composition may have been attributable to the short duration of the study, as microbial composition and maturation of subgingival biofilms require an extended period to reflect a significant shift (Quirynen *et al.*, 1993). Overall, the studies mentioned above indicate that the rougher a surface is intra-orally, the greater the amount of bacterial accumulation occurs above 0.2 μm , although bacterial adherence does not seem to be affected below this threshold.

Studies which used IP as a treatment modality in a tabletop setting on discs provide the operator with unobstructed access to the surface allocated for treatment (Tawse-Smith *et al.*, 2016; Toma *et al.*, 2018; Beheshti Maal *et al.*, 2020; Yildiz *et al.*, 2022; Vierling *et al.*, 2024). All IP procedures result in a substantial reduction of surface roughness compared to sandblasted, acid-etched surfaces or other surfaces of similar roughness, which may suggest that baseline surface characteristics have a limited impact on the final surface roughness (Tawse-Smith *et al.*, 2016; Toma *et al.*, 2018; Beheshti Maal *et al.*, 2020; Yildiz *et al.*, 2022; Vierling *et al.*, 2024). IP with a polishing bur sequence typically achieves Ra values below 0.5 μm and Sa values of 0.2 to 0.4 μm (Tawse-Smith *et al.*, 2016; Beheshti Maal *et al.*, 2020; Yildiz *et al.*, 2022). Tungsten carbide burs, followed by silicone polishers, appear to produce the smoothest Ra values ($< 0.2\mu\text{m}$) (Yildiz *et al.*, 2022). Without a polishing sequence, the average surface roughness is significantly higher (Tawse-Smith *et al.*, 2016; Toma *et al.*, 2018; Beheshti Maal *et al.*, 2020; Yildiz *et al.*, 2022). Vierling *et al.* (2024) noted that diamond burs tend to leave more irregular, rougher surfaces compared to tungsten carbide burs.

In a number of published articles, a predetermined maximum pressure was applied to the disc surfaces using a pressure-controlled rotary, which again may not be representative of the clinical scenario (Toma *et al.*, 2018; Beheshti Maal *et al.*, 2020; Vierling *et al.*, 2024). These studies demonstrate that when IP is performed on titanium discs, the selection of burs and subsequent polishing play a crucial role in determining the final surface characteristics. Existing evidence suggests that tungsten carbide burs, followed by silicone polishers produce the lowest roughness values, sometimes achieving roughness levels similar or lower than turned (machined controls) (Yildiz *et al.*, 2022). However, the findings from the aforementioned studies should be interpreted with caution, as they may not be directly applicable to screw-type dental implants due to the lack of implant-specific shape and macro-design features.

In vitro investigations using moderately rough implants on a tabletop model showed consistently reduced surface roughness following IP, although the smoothness achieved

was highly dependent on the bur protocol or instrument used (Meier *et al.*, 2012; Ramel *et al.*, 2015; de Souza Júnior *et al.*, 2016; Costa-Berenguer *et al.*, 2017; Sivoilella *et al.*, 2021; Camps-Font *et al.*, 2023; Tsampli *et al.*, 2024). Costa-Berenguer *et al.* (2017) achieved a Sa of 0.1 μm and Sz of 3.67 μm after the use of a tungsten carbide bur with silicone carbide polishers. However, the same bur protocol was repeated by Camps-Font *et al.* (2023), which found an increased final surface roughness on grade V titanium implants of Sa of 0.16 μm and Sz of 4.16 μm . This difference between the studies may have been attributable to differing implant titanium grade or a difference in the operator's experience level. Ramel *et al.* (2015) found that a diamond bur protocol with reducing grit size, followed by silicone polishers, achieved a Ra of 0.32 μm and Rz of 2.31 μm . However, the level of roughness did not reach that of the control, being a smooth, polished implant neck which had a Ra of 0.10 μm and Rz of 0.81 μm (Ramel *et al.*, 2015). Meier *et al.* (2012) identified a trend that conical burs achieved smoother surfaces in comparison to cylindrical burs.

Polishing significantly reduced the final average surface roughness compared to the pre-polish values when only burs were used (Costa-Berenguer *et al.*, 2017; Camps-Font *et al.*, 2023). Some of these studies did not include a polishing step in the IP bur protocol (Meier *et al.*, 2012; Sivoilella *et al.*, 2021; Tsampli *et al.*, 2024). Sivoilella *et al.* (2021) used carbide burs and achieved a Ra of 0.9 μm and Rz of 4.3 μm , while Tsampli *et al.* (2024) used diamond burs, which resulted in a Ra of 0.78 μm , Sa of 0.85 μm and Sz of 13.74 μm on the implant surfaces after IP. Both of these studies used sonic instruments as a comparator group, which consistently showed a significantly lower surface roughness achieved after IP compared to when diamond and carbide burs were utilised (Sivoilella *et al.*, 2021; Tsampli *et al.*, 2024).

The majority of the studies used pressure-controlled customised jigs, which again are not representative of a clinical scenario (Meier *et al.*, 2012; de Souza Júnior *et al.*, 2016; Costa-Berenguer *et al.*, 2017; Sivoilella *et al.*, 2021; Tsampli *et al.*, 2024). These studies show that both operator-dependent factors and equipment variability contribute substantially to the surface outcomes of IP protocols, along with the use of a polishing

step in the IP protocol.

IP procedures performed in a tabletop setting on implants and discs allow for a controlled setting, allowing for an accurate assessment of which instrumentation protocols may provide the most favourable result for surface roughness. However, in a clinical scenario, variables such as implant location, presence of adjacent teeth and prosthetic restorations may significantly hinder the ability to achieve optimal surface smoothness and may compromise the overall effectiveness of IP. The use of phantom head models allows researchers to emulate clinical conditions, providing an assessment of IP in a simulated environment (Rimondini *et al.*, 2000; Sahrmann *et al.*, 2019; Burgueño-Barris *et al.*, 2023). Rimondini *et al.* (2000) used a phantom head model on plasma-sprayed implants using bladed tungsten carbide burs and diamond burs of various grits. Diamond burs with reducing grit sizes of 30 μm and 15 μm achieved a Ra of $1.04 \pm 0.14 \mu\text{m}$ and Rz of $4.86 \pm 0.57 \mu\text{m}$, while a combination of carbide burs achieved a comparable Ra of $1.16 \pm 0.26 \mu\text{m}$ and Rz of $4.04 \pm 0.83 \mu\text{m}$ (Rimondini *et al.*, 2000). However, no subsequent step in polishing was completed, and the phantom head described did not appear to emulate clinical conditions such as neighbouring teeth, soft tissues, the form of a dental arch, or the location in the arch in which the implants were placed (Rimondini, Cicognani Simoncini and Carrassi, 2000).

Sahrmann *et al.* (2019) performed an *in vitro* study using phantom heads using stone models with implants placed in the 1-6 or 2-6 sites. The bur protocol was randomised for the implant location, and the model had adjacent teeth, but no soft tissue model was present (Sahrmann *et al.*, 2019). Diamond burs of decreasing grit size (106 μm to 40 μm), followed by polishing with Arkansas stone burs, resulted in a Ra of $0.76 \pm 0.14 \mu\text{m}$ while Rz was $4.12 \pm 0.72 \mu\text{m}$. The silicon carbide stones bur achieved a Ra of $0.38 \pm 0.15 \mu\text{m}$, and a Rz of $1.87 \pm 0.69 \mu\text{m}$. The roughness values for the silicone carbide bur group were significantly lower compared to the diamond bur ($p < 0.001$) (Sahrmann *et al.*, 2019). This study demonstrated that the bur protocol used directly influenced the final surface roughness under clinically simulated conditions (Sahrmann *et al.*, 2019).

Burgueño-Barris *et al.* (2023) used a phantom head with a soft tissue model with adjacent teeth. Implants were in either favourable situations or unfavourable situations. IP was performed with an oval tungsten carbide bur and two silicone carbide polishers. The resultant surface roughness was significantly reduced (Sa: 0.60 SD 0.14; Sz: 1.83 SD 0.10) compared to baseline implant surface roughness levels (Sa: 1.83 SD 0.10; Sz: 37.78 SD 0.35) ($p < 0.001$) (Burgueño-Barris *et al.*, 2023). The IP surfaces were significantly rougher than polished control surfaces (Sa: 0.24 SD 0.01; Sz: 4.46 SD 0.15) ($p < 0.001$). Surface roughness was significantly higher in the unfavourable situation than in the favourable group (Sa: MD = 0.16; 95% CI = 0.10 to 0.21; Sz: MD = 4.86; 95% CI = 3.42 to 6.29), along with significantly longer treatment times ($p < 0.05$). Furthermore, the presence of a prosthetic crown on the implants led to an increased number of residual implant threads after IP (OR = 7.0; 95% CI = 3.5 to 13.99; $p < 0.001$) (Burgueño-Barris *et al.*, 2023). This study highlighted that restricted access is associated with increased surface roughness following IP, indicating that anatomical constraints at specific sites may hinder the procedure's efficacy.

Overall, clinical variables such as implant location, presence of adjacent teeth and prosthetic restorations significantly hinder the ability to achieve optimal surface smoothness and may compromise the overall effectiveness of IP (Burgueño-Barris *et al.*, 2023). In addition, the selection of burs used also appears to influence the final surface roughness (Sahrman *et al.*, 2019). Furthermore, the surface roughness of the treated surfaces was significantly smoother than the surface roughness of dental implants at baseline (Sahrman *et al.*, 2019). These findings suggest that IP reducing surface roughness to clinically desirable thresholds (e.g., $Ra < 0.2 \mu m$) remains challenging in anatomically constrained sites (Bollen *et al.*, 1996; Rimondini *et al.*, 2000; Sahrman *et al.*, 2019).

Currently, there is a trend in the literature for smoother surface roughness achieved on implants when IP is performed in a tabletop model, when compared to the results of phantom head models. However, there are no comparative studies in the literature which examine surface roughness after IP in a phantom head model and tabletop model

while using the same bur protocol. Our research aimed to assess how operator access influenced IP for surface roughness (Ra and Rz) and material loss achieved on dental implant surfaces, when using the same bur protocol in a tabletop and phantom head setting.

The results of the study herein show a significantly increased median Ra surface roughness on implants prepared in the phantom head setting of 0.53 μm (IQR: 0.49 – 0.58 μm) compared to that in the tabletop setting of 0.44 μm (IQR: 0.37 – 0.62 μm) ($p = 0.004$). In addition, implants in the phantom model had a significantly increased median Rz value of 2.78 μm (IQR: 2.56 – 3.01 μm) compared to 2.47 μm (IQR: 1.98 – 2.75 μm) ($p = 0.019$) for implants found in the tabletop model. Based on these findings, we rejected the null hypothesis and found evidence supporting the alternative hypothesis that the surface roughness (Ra and Rz) differed between the phantom head and tabletop models.

The surface roughness results of our study were markedly lower than the Ra and Rz found by Rimondini, *et al.* (2000) and the diamond bur group in Sahrman *et al.* (2019), with both of these studies using a phantom head design. The phantom head study of Burgueño-Barris *et al.* (2023) could not be directly compared to our findings, as they used Sa and Sz outcome measures, which are not directly comparable to Ra and Rz used in our study (Dagnall, 2011). A similar bur protocol of tungsten carbide burs and silicone polishers was used to perform IP on discs in an *in vitro* study by Yildiz *et al.* (2022). Yildiz *et al.* (2022) reported surface roughness values ranging between 0.13–0.14 μm (Ra) and an Rz of 0.69 μm following the use of a similar IP protocol. While our study demonstrated relatively low roughness values within a phantom head setting, the smoother surfaces observed in disc-based tabletop models using similar bur sequences are noteworthy. This discrepancy may be attributed to enhanced instrumentation access or the inherently flat geometry of discs, which contrasts with the complex macrostructure of dental implants that may hinder uniform surface finishing. In addition, our findings agree with prior studies in demonstrating that IP significantly reduces implant surface roughness relative to the original rough state (Ramel *et al.*,

2015; Camps-Font *et al.*, 2023; Tsampli *et al.*, 2024).

A “threshold Ra” of 0.2 μm has been associated with having no significant impact on supra- or subgingival plaque composition (Bollen *et al.*, 1996; Quirynen *et al.*, 1996). This threshold represents the lower limit at which, if a surface becomes smoother, it will not have an impact on the bacterial composition found. However, while our study did not achieve or did not fall below this threshold, surfaces with increasing surface roughness appear to increase bacterial adhesion in an increasing pattern, a “surface roughness gradient” so to speak. Quirynen *et al.* (1993) showed there was an increased plaque accumulation of rough implant abutment with an Ra of $0.81 \pm 0.1 \mu\text{m}$ compared to smooth abutments with an Ra of $0.35 \pm 0.03 \mu\text{m}$ after three months. Azzola *et al.* (2020) and Bertl *et al.* (2024) found that for surfaces that had undergone IP and that were housed in intra-oral trays, IP surfaces had significantly less bacterial plaque accumulation and less mature biofilm formation compared to those found on moderately rough surfaces. However, both of these studies had a short follow-up period of a matter of days, which may not produce representative long-term results, and they did not measure the surface roughness of the implants treated with IP (Azzola *et al.*, 2020; Bertl *et al.*, 2024). In addition, an *in vitro* multispecies biofilm model used in Bermejo *et al.* (2019) showed that titanium surfaces with minimal-roughness (Sa 0.5–1 μm) had significantly less bacterial plaque after 96 hours of incubation compared to surfaces with moderate-roughness (Sa 1–2 μm). This shows that although our study did not reach the “threshold Ra” of 0.2 μm , the surface roughness achieved in our model would be associated with reduced plaque adhesion and maturation of biofilm.

Romeo *et al.* (2005) performed a randomised control trial and found after 24 months of follow-up that PD, PAL, and modified bleeding index were significantly higher in the control group than in the IP group, along with increased implant losses. In addition, favourable clinical outcomes of reduced BoP and PD of 67% and 2.5mm, respectively, were noted by Bianchini *et al.* (2024). However, a recent randomised controlled clinical trial found that the adjunctive use of IP with access surgery and debridement showed no significant difference between treatment groups (Cruz *et al.*, 2025). Our study

investigated whether there was an immediate difference in the structure of the treated implants *in vitro*, with no ability to assess long-term clinical outcomes. However, the available clinical evidence indicates the ultimate impact on patient outcomes is variable and must still be verified by future research (Romeo *et al.*, 2005; Bianchini *et al.*, 2024; Cruz *et al.*, 2025). Currently, there is a lack of evidence to recommend the use of IP in clinical practice so further research is required for the effect of IP is to be evaluated (Herrera *et al.*, 2023; Ramanauskaite *et al.*, 2023). In addition, the link between *in vitro* surface roughness and successful clinical peri-implant outcomes has not been proven in the literature.

The average time required for IP of implants in the study herein was significantly increased in the phantom head model (765 sec) compared to the tabletop setting (685 sec) ($p < 0.001$). The overall time required for IP in our study was similar to that of Sahrman *et al.* (2019) and Jorio *et al.* (2021). However, in contrast to Sahrman *et al.* (2019), our study did not have an allocated amount of time for the use of the two tungsten carbide burs and polishing with silicone carbide polishers, and so the total time required to perform IP was measured. In addition, the time required for IP was much less in Burgueño-Barris *et al.* (2023), with a median time of 400 seconds. Of interest is the finding that although the preparation time was longer for the phantom head model implants, this did not lead to a further reduction in Ra or Rz. In contrast to the study herein and in a clinical scenario, a clinician would additionally have to manage soft tissues and bleeding, along with patient behaviour, all of which may further increase the treatment time required. In addition, local factors to the implant, such as the presence of a crown, may impact IP outcomes along with the time necessary to complete the procedure (Burgueño-Barris *et al.*, 2023). There is also potential that prolonged IP may increase the risk of thermal insult to the peri-implant tissues (de Souza Júnior *et al.*, 2016). In addition, IP is used in tandem with other surgical techniques, and so if a patient has multiple implants requiring IP, this should be factored into surgical time and the requirement for adequate anaesthesia if the procedure will be prolonged (Schwarz *et al.*, 2022). The study herein demonstrated that limited access requires more time for

preparation. However, this increased time does not necessarily lead to a lower surface roughness.

There was no significant difference in mass reduction reported in our study after IP between implants which had been prepared in the phantom head and tabletop, which ranged from 0.03 to 0.04 g. These findings are surprising, as a larger reduction in mass was expected in the phantom head model due to limited access. However, this may have been compensated for by an increased operative time to allow the operator to more carefully alter the implant surface. Compared to the mean mass reduction in the study herein, another similar study demonstrated a mean mass loss range of 0.02 – 0.025 g, which may have been attributable to the diamond bur protocol used or the implant type used (Sahrmann *et al.*, 2019). However, the mass loss observed with similar tungsten carbide burs in our study is consistent with the findings reported in the existing literature (Sivolella *et al.*, 2021; Tsampli *et al.*, 2024).

The study herein was the first in the literature to look at material loss of differing implant types using the same bur protocol. The findings demonstrated that Straumann® implants had a significant mass reduction in comparison to Ankylos® ($p < 0.001$) and Sweden & Martina® implants ($p < 0.001$). No significant differences were found for mass reduction between Ankylos® and Sweden & Martina® implants ($p = 0.649$). Straumann® implants exhibited the most significant reduction in width, significantly more than both Ankylos® ($p < 0.001$) and Sweden & Martina® implants ($p < 0.001$). In contrast, Ankylos® implants showed the smallest width reduction, which was significantly less than that of Sweden & Martina® implants ($p < 0.001$). These differences in width and mass changes between the implant groups are interrelated due to the material loss occurring. The difference between implant types was most likely due to the different thread design, pitch and depth, along with the initial implant diameter at baseline. All of these components would lead to a greater implant surface area, which would require increased materials loss, such as that seen for the width and mass change in Straumann® implants. The Straumann® implants had the greatest initial width and lowest thread

pitch, which would require an increased amount of material removal to perform IP to a satisfactory level.

Differences between width and mass reduction across the implant types did not differ between the phantom head and tabletop settings ($p > 0.05$). The width reduction of implants was 0.69 mm and 0.81 mm in the phantom head model and tabletop model, respectively. The residual wall thickness of the implant after IP can be impacted by the use of differing bur protocols (Sahrmann *et al.*, 2019; Stavropoulos *et al.*, 2023). In the study by Sahrmann *et al.* (2019), residual wall thickness was measured radiographically, which resulted in a 0.25-0.3mm loss on each side of the implant. Similarly, Tsampli *et al.* (2024) found a decrease in radius reduction of implants in a tabletop model when using tungsten carbide burs and airscaler of -178 μm (-0.178 mm) and -30 μm (-0.030 mm), respectively. This finding is far below that of our study, although IP was performed using a fixed jig with constant pressure application. However, this finding is similar to that found in Sivoilella *et al.* (2021), which performed IP freehand in a tabletop model.

Overall, clinicians should aim to remove as little material as necessary to achieve a smooth surface after IP. Our findings suggest that material loss across the settings does not differ, although differences are present when different implants are used. IP involves the decontamination and smoothing of the implant surface (Schwarz *et al.*, 2022). However, soft tissue considerations of the biological width and epithelial seal should be considered when preparing the implant surface. Atsuta *et al.* (2019) performed a study on rats, which found that a “step-type” implant may improve epithelial sealing as well as reduce apical peri-implant epithelial down-growth. In addition, the presence of a roughened implant surface negatively impacts the proliferation and the attachment of fibroblasts on titanium surfaces compared to smooth surfaces (Könönen *et al.*, 1992; Mustafa *et al.*, 1998; Beheshti Maal *et al.*, 2020). Based on this, preserving or creating a notch near the expected soft tissue margin during the IP procedure may in theory be attempted to promote an improved seal. However, the width of the implant and the surface roughness after IP should not be compromised after IP is completed. Prior to IP

of implants, macro-geometry and width should be taken into account to plan the IP and to account for potential complications such as the risk of implant fracture in narrow diameter implants (Chan *et al.*, 2013; Bertl *et al.*, 2021).

Our study took a preliminary step toward assessing how implant macro-design may affect IP outcomes by using implant systems with different coronal designs and mimicking real-world variation of implant design. The implants differed from one another, being either tissue-level with a divergent or convergent neck, or bone-level. However, our study failed to show any statistically significant difference in the final surface roughness achieved for Ra ($p = 0.620$) and Rz ($p = 0.473$) for the implant types assessed. This finding may allude to the possibility that the final surface roughness of an IP procedure is independent of baseline implant surface roughness and treatment, along with the macro geometry of the implant. However, our sample size for each implant type was relatively small, which means smaller differences between implant groups may not have reached the level of statistical significance.

Further findings from the study herein showed that the surface roughness of the buccal and lingual surfaces of implants treated in the phantom head setting overall did not show any significant differences for Ra and Rz ($p > 0.05$). These findings are similar to that of Burgueño-Barris *et al.* (2023), which found that using a phantom head study, the surface roughness achieved on different aspects of an implant were similar. However, this study did indicate that the location within the mouth and the presence of adjacent teeth can have an impact on final surface roughness (Burgueño-Barris *et al.*, 2023). However, literature in this area is sparse, and our study builds upon this finding. Although in a surgery, one would anticipate that lingual aspects would be more challenging to visualise and be more difficult to isolate due to the presence of the tongue compared to buccal aspects. However, our study did not time the preparation of the buccal and lingual aspects separately, which may have differed. Although our study found no differences in roughness between buccal and lingual surfaces, clinicians should remain vigilant that, in a clinical setting, these surfaces may be more challenging and limit ideal outcomes. Finally, there were no significant differences for the Ra and Rz

values between the Straumann®, Ankylos® and Sweden & Martina® implants when only the implants prepared in the phantom head setting were examined ($p > 0.05$).

When performing IP, clinicians should be cautious about excessive removal of implant material to achieve a smooth surface. It has been proposed that implants with an external connection may be less prone to implant fracture compared to those with internal connections due to greater residual thickness of implant material (Camps-Font *et al.*, 2023). It is recommended to avoid overzealous reduction of internal connection implants during IP (Costa-Berenguer *et al.*, 2017; Camps-Font *et al.*, 2023). Implants after IP with narrower diameters have been shown to have a reduced load required for fracture (Chan *et al.*, 2013; Bertl *et al.*, 2021). In addition, the risk of narrow implant fracture appears to be increased if it is a tissue-level implant compared to a bone-level implant when simulated advanced horizontal bone loss is present (e.g. 5mm) (Stavropoulos *et al.*, 2023). Overall, IP should be performed cautiously in an attempt to preserve the structural integrity of the implant in question (Stavropoulos *et al.*, 2019).

Clinicians should also be aware of the alteration of surface chemistry along with a reduced resistance to corrosion for altered implant surfaces (Schwarz *et al.*, 2016; Beheshti Maal *et al.*, 2020; Sivolella *et al.*, 2021; Camps-Font *et al.*, 2023). In addition, smoothened titanium surfaces appear to have an improved cellular response of fibroblasts and osteoblasts *in vitro* compared to moderately roughened surfaces (Toma *et al.*, 2016; Beheshti Maal *et al.*, 2020). Based on these findings, clinicians should aim to achieve a smooth surface not only for reduced plaque retention but also for improved cellular responses. During IP, there is a release of titanium particles, which are released into the surrounding tissues (Suárez-López *et al.*, 2018). The release of Ti-6Al-4V particles appears to elicit a cytotoxic effect compared to grade IV titanium after IP (Barrak *et al.*, 2020). However, the use of IP does not seem to produce an inflammatory effect on the tissues clinically (Beheshti Maal and Verket, 2022). Nevertheless, there is concern over the potential for systemic decimation of titanium particles and their effects in the long term (Barrak *et al.*, 2020). Finally, during the IP procedure, heat may be generated, which has been flagged as a potential cause of thermal osteonecrosis

(Stavropoulos *et al.*, 2019).

There are several limitations of our study which may influence the results we found. Firstly, the in vitro nature of the study was performed in phantom heads to limit access to the operator. However, this study does not fully replicate clinical challenges that would be present in a real patient. This includes the presence of bleeding and saliva in patients, along with movement and the presence of a tongue. These factors may lead to a less optimal result in a clinical setting. In addition, our study did not have a soft tissue model present around the dental implants, which would have more accurately mirrored the need for tissue reflection of tissues in patients.

The implants in our study did not have implant restorations present, and all the implants were affected by a 5mm horizontal implant defect with no adjacent teeth. This limits the generalisability of our study to cases which may have those factors in clinical practice. It has already been shown that the presence of a crown can result in increased residual threads in a phantom head study with a soft tissue model present (Burgueño-Barris *et al.*, 2023).

A single operator performed IP of all implants in our study. Although a sole operator was used to reduce variability within our research, this also reduces the generalisability of the results. Individual operator skill and technique vary, with some clinicians potentially being able to achieve improved results. In addition, the application of pressure was not controlled for when performing IP on the dental implants on the phantom head and tabletop models. In this way, it attempted to reproduce the real-world conditions present in a patient's mouth. However, this lack of pressure control means that our outcomes, while generally repeatable by the same operator, might differ if another operator performs the procedure.

A final limitation of this study is that the power calculation was based on a study that was not directly comparable in methodology to our research (Sahrman *et al.*, 2019).

Additionally, there was a small number of implants used for comparisons between the three different implant systems.

Future research should investigate how the presence of different morphologies of peri-implant defects, the presence of implant restoration, and the use of a soft tissue model would affect outcomes of IP. An alternative approach to using a phantom head could be to use a cadaver model to simulate clinical conditions more closely to live patients. With the improvement of intra-oral scanning, clinical studies in the future may be able to scan implant surfaces intra-operatively to assess implant surface topography and provide clinicians with real-time information as to the roughness achieved after IP. However, no studies have evaluated whether this is an accurate and valid approach. This approach may then allow researchers to correlate surface roughness with the clinical outcomes of the implants while still present within the patient's mouth. Alternatively, explanted implants which had undergone IP can have their surface examined under profilometry, as in (Geremias *et al.*, 2017). However, this may introduce failure bias as the implants which are successful within the patient's mouth could not be examined, and so the characteristics of these would not be able to be assessed.

5 Conclusions

This in-vitro study aimed to evaluate whether accessibility to the implant during implantoplasty (IP) has a significant effect on surface roughness and material loss by comparing results obtained using a phantom head model versus a tabletop setup. Additionally, it sought to compare the surface roughness and material loss produced by IP across three commercially available dental implant systems, and to examine potential differences between the buccal and lingual surfaces of implants treated in the phantom head model.

Implants treated with IP in a phantom head model had a significantly increased surface roughness and required more time to complete the procedure. This increased duration may be attributed to the added complexity and limited access associated with working within a simulated intraoral environment compared to the control (tabletop) setting.

Interestingly, no significant differences in final surface roughness were observed between the different implant types following IP. This suggests that the baseline surface and anatomical characteristics of an implant may not significantly influence the final surface roughness after the procedure. Significant differences were found between implant types for mass and width change overall, which may be due to the macro-geometry and thread design at baseline. Clinicians should be cautious when performing IP to prevent the overzealous width reduction on narrow implants, along with those implant designs which may lead to a reduced width or residual wall thickness, and ultimately a reduced fracture resistance (Sahrman *et al.*, 2019; Stavropoulos *et al.*, 2023). In addition, no significant differences in Ra and Rz were found between the buccal and lingual aspects of the implants in the phantom head setting. However, clinicians should anticipate that in a clinical scenario, lingual surfaces could be more challenging to isolate and visualise due to the presence of the tongue and lingual tissues.

Currently, IP for implant surface decontamination during the surgical management of peri-implantitis is not recommended due to limited evidence supporting its use (Herrera

et al., 2023; Ramanauskaite *et al.*, 2023). Further research is required to correlate the final surface roughness achieved clinically with the long-term peri-implant clinical outcomes of the patient. However, this will be challenging given the limitations of current technology.

6 References

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7 Appendices

7.1 Appendix 1

Implant Number	Implant type	IP Location
Implant No 1	Straumann® Tissue Level Tapered Effect Implant SLA 4.1x12mm RN	Tabletop
Implant No 2	Ankylos® Bone Level Implant ø 3.5 x 14mm	Tabletop
Implant No 3	Sweden & Martina® PRAMA FR ZIRTI ø 3.8x13mm	Tabletop
Implant No 4	Straumann® Tissue Level Tapered Effect Implant SLA 4.1x12mm RN	Phantom head
Implant No 5	Ankylos® Bone Level Implant ø 3.5 x 14mm	Phantom head
Implant No 6	Sweden & Martina® PRAMA FR ZIRTI ø 3.8x13mm	Phantom head
Implant No 7	Straumann® Tissue Level Tapered Effect Implant SLA 4.1x12mm RN	Tabletop
Implant No 8	Ankylos® Bone Level Implant ø 3.5 x 14mm	Tabletop
Implant No 9	Sweden & Martina® PRAMA FR ZIRTI ø 3.8x13mm	Tabletop
Implant No 10	Straumann® Tissue Level Tapered Effect Implant SLA 4.1x12mm RN	Phantom head
Implant No 11	Ankylos® Bone Level Implant ø 3.5 x 14mm	Phantom head
Implant No 12	Sweden & Martina® PRAMA FR ZIRTI ø 3.8x13mm	Phantom head
Implant No 13	Straumann® Tissue Level Tapered Effect Implant SLA 4.1x12mm RN	Tabletop
Implant No 14	Ankylos® Bone Level Implant ø 3.5 x 14mm	Tabletop
Implant No 15	Sweden & Martina® PRAMA FR ZIRTI ø 3.8x13mm	Tabletop
Implant No 16	Straumann® Tissue Level Tapered Effect Implant SLA 4.1x12mm RN	Phantom head
Implant No 17	Ankylos® Bone Level Implant ø 3.5 x 14mm	Phantom head
Implant No 18	Sweden & Martina® PRAMA FR ZIRTI ø 3.8x13mm	Phantom head
Implant No 19	Straumann® Tissue Level Tapered Effect Implant SLA 4.1x12mm RN	Tabletop
Implant No 20	Ankylos® Bone Level Implant ø 3.5 x 14mm	Tabletop
Implant No 21	Sweden & Martina® PRAMA FR ZIRTI ø 3.8x13mm	Tabletop
Implant No 22	Straumann® Tissue Level Tapered Effect Implant SLA 4.1x12mm RN	Phantom head
Implant No 23	Ankylos® Bone Level Implant ø 3.5 x 14mm	Phantom head
Implant No 24	Sweden & Martina® PRAMA FR ZIRTI ø 3.8x13mm	Phantom head
Implant No 25	Straumann® Tissue Level Tapered Effect Implant SLA 4.1x12mm RN	Tabletop
Implant No 26	Ankylos® Bone Level Implant ø 3.5 x 14mm	Tabletop
Implant No 27	Sweden & Martina® PRAMA FR ZIRTI ø 3.8x13mm	Tabletop
Implant No 28	Straumann® Tissue Level Tapered Effect Implant SLA 4.1x12mm RN	Phantom head
Implant No 29	Ankylos® Bone Level Implant ø 3.5 x 14mm	Phantom head
Implant No 30	Sweden & Martina® PRAMA FR ZIRTI ø 3.8x13mm	Phantom head
Implant No 31	Straumann® Tissue Level Tapered Effect Implant SLA 4.1x12mm RN	Tabletop
Implant No 32	Ankylos® Bone Level Implant ø 3.5 x 14mm	Tabletop
Implant No 33	Sweden & Martina® PRAMA FR ZIRTI ø 3.8x13mm	Tabletop
Implant No 34	Straumann® Tissue Level Tapered Effect Implant SLA 4.1x12mm RN	Phantom head
Implant No 35	Ankylos® Bone Level Implant ø 3.5 x 14mm	Phantom head
Implant No 36	Sweden & Martina® PRAMA FR ZIRTI ø 3.8x13mm	Phantom head
Implant No 37	Straumann® Tissue Level Tapered Effect Implant SLA 4.1x12mm RN	Tabletop
Implant No 38	Ankylos® Bone Level Implant ø 3.5 x 14mm	Tabletop
Implant No 39	Sweden & Martina® PRAMA FR ZIRTI ø 3.8x13mm	Tabletop
Implant No 40	Straumann® Tissue Level Tapered Effect Implant SLA 4.1x12mm RN	Phantom head
Implant No 41	Ankylos® Bone Level Implant ø 3.5 x 14mm	Phantom head
Implant No 42	Sweden & Martina® PRAMA FR ZIRTI ø 3.8x13mm	Phantom head

7.2 Appendix 2

TABLE 1. Modified CONSORT checklist of items for reporting in vitro studies of dental materials

Section/topic	Checklist item
Abstract	Item 1. Structured summary of trial design, methods, results, and conclusions
Introduction	
<i>Background and objectives</i>	- Item 2a. Scientific background and explanation of rationale - Item 2b. Specific objectives and/or hypotheses
Methods	
<i>Intervention</i>	Item 3. The intervention for each group, including how and when it was administered, with sufficient detail to enable replication
<i>Outcomes</i>	Item 4. Completely defined, pre-specified primary and secondary measures of outcome, including how and when they were assessed
<i>Sample size</i>	Item 5. How sample size was determined
<i>Randomization: Sequence generation</i>	Item 6. Method used to generate the random allocation sequence
<i>Allocation concealment mechanism</i>	Item 7. Mechanism used to implement the random allocation sequence (for example, sequentially numbered containers), describing any steps taken to conceal the sequence until intervention was assigned
<i>Implementation</i>	Item 8. Who generated the random allocation sequence, who enrolled teeth, and who assigned teeth to intervention
<i>Blinding</i>	Item 9. If done, who was blinded after assignment to intervention (for example, care providers, those assessing outcomes), and how
<i>Statistical methods</i>	Item 10. Statistical methods used to compare groups for primary and secondary outcomes
Results	
<i>Outcomes and estimation</i>	Item 11. For each primary and secondary outcome, results for each group, and the estimated size of the effect and its precision (for example 95% confidence interval)
Discussion	
<i>Limitations</i>	Item 12. Trial limitations, addressing sources of potential bias, imprecision, and, if relevant, multiplicity of analyses
Other information	
<i>Funding</i>	Item 13. Sources of funding and other support (for example suppliers of drugs), role of funders
<i>Protocol</i>	Item 14. Where the full trial protocol can be accessed, if available