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Depth of reading within the gingival sulcus of intraoral scanners: in vitro study

Dissertação apresentada à Universidade Católica Portuguesa
para obtenção do grau de Mestre em Medicina Dentária

Por:
Marie Christine Scarano Paes Rosa

Viseu, 2026

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Dedication

"For I can do everything through Christ, who gives me strength" (Philippians 4.13)

To God, the creator of my life for guiding me, sustaining me, and granting me the grace to live and fulfill this purpose through him.

To my parents, for their unconditional love, sacrifices, and unwavering support forever and always.

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First and above all, I give all the glory and thanks to God, who is the foundation of my life. Throughout this journey, His presence reminded me that I was never alone, and lifted my hopes in moments of doubt. Every achievement was only possible through His grace. More than a strength in the toughest moments He is the purpose behind everything that I do , and for that, my deepest gratitude will always belong to Him.

To my parents, Leo e Anne, there are no words capable of expressing the depth of my gratitude for everything you have done for me. I will always be grateful for every sacrifice made in silence, you placed my dreams above your own, for every moment in which you believed in me even when I doubted myself. Everything I am today, reflects everything you ever thought me, your values, unconditional love, and resilience. This achievement is as much yours as it is mine.

To my fiancé, Lucas, thank you for being by my side and my safe place through most of this journey. Thank you for your patience during the most exhausting and doubtful days, for your unwavering belief in me that made the worst part better. I am deeply grateful not only for everything you have done for me during these years, but also for the life we are building together. Ending this journey almost as your wife is one of the best achievements of my life. I thank God for bringing you into my life.

To my future parents-in-law, thank you for welcoming me with kindness, support, and affection. Your support through these years meant more than you could ever realize. I am deeply grateful to become part of your family.

To my dear friends, especially my “sambinha” friends, thank you for making those five years more memorable, it wouldn’t have been the same without you. Thank you for the growth we experienced together, turning us into better persons. I truly believe that some people come into our lives for a reason, and I will forever be grateful that our paths crossed.

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I also would like to thank all the professors and staff of this faculty, your commitment to education and support throughout these years have contributed greatly to my academic and personal growth.

Finally, I would like to dedicate a special thought to my grandmother, who passed away only a few months before my graduation. Although I wished we had shared more time together, losing her so close to this important moment was one of the greatest sorrows of my journey. As I reached this achievement, I cannot help but wish she were here to see it, and I still hope she is smiling and proud of me.

Resumo

Introdução: A captura precisa das margens subgengivais é essencial para as restaurações indiretas, mas continua a ser um desafio para os atuais scanners intraorais.

Objetivo:
Avaliar a profundidade de leitura, bem como a precisão e a exatidão de três scanners intraorais (Primescan, Trios 4 e Trios 6) na preparação subgengival, com dois tipos diferentes de preparação dentária e espaço gengival.

Materiais e Métodos:
Dois modelos impressos em 3D, um com uma preparação do tipo vertical no canino e outro com uma preparação do tipo horizontal no molar, ambos com uma margem subgengival de 2 mm. Um modelo simulou um espaçamento de 0,25 mm e o outro um espaçamento de 0,5 mm. Cada modelo foi digitalizado 10 vezes com cada scanner. A profundidade de leitura foi avaliada através de medições lineares obtidas com o Autodesk Fusion 360 em seis locais predefinidos na área vestibular e seis na área palatina. A precisão foi avaliada com a análise do desvio quadrático médio utilizando o Geomagic Control X. A análise estatística foi realizada com um nível de significância de $p < 0,05$.

Resultados:
O Primescan apresentou uma profundidade de leitura significativamente maior do que ambos os scanners Trios, particularmente no intervalo de 0,25 mm, atingindo uma profundidade média de 1,23 mm, em comparação com 0,61 mm para o Trios 6 e 0,38 mm para o Trios 4. No entanto, o desempenho dos scanners melhorou com o aumento do intervalo de 0,25 mm para 0,5 mm. No entanto, os scanners Trios demonstraram valores RMS mais baixos do que o Primescan; estes valores mais baixos estiveram associados a uma penetração e leituras subgengivais reduzidas do scanner. O que sugere que o RMS, por si só, pode não representar adequadamente o desempenho do scanner, principalmente em áreas subgengivais. A preparação horizontal também apresentou maior

dificuldade de digitalização do que a preparação vertical, com valores RMS mais elevados e profundidades de leitura mais baixas.

Conclusão:

O desempenho do scanner na área subgengival é afetado por vários fatores, principalmente a largura do sulco gengival, a geometria da preparação e o maior ou menor grau de afastamento gengival se feito. O Primescan demonstrou uma profundidade de leitura superior, enquanto os scanners Trios apresentaram valores RMS mais baixos. Os resultados sugerem que o desempenho do scanner deve ser avaliado tendo em conta a exatidão e a aquisição de dados.

Palavras-Chave:

Scanners Intraorais, Impressões Digitais, Margem Subgengivais, Exatidão

Abstract

Introduction:

Capturing subgingival margins accurately is essential for indirect restorations but remains challenging for current intraoral scanners.

Objective:

Evaluate the depth of Reading and both accuracy of three intraoral scanners (Primescan, Trios 4 and Trios 6) in subgingival preparation with two different tooth preparation and gingival gap.

Materials and Methods:

Two 3D-printed models with one vertical preparation on the canine and one horizontal preparation on the molar both with 2mm subgingival margin. One model simulated with a gap of 0.25mm and one with a 0.5mm gap. Each model was scanned 10 times with each scanner. Depth of reading was assessed through linear measurements obtained with Autodesk Fusion 360 at six predefined locations in the buccal area and six at the palatal area. Accuracy was evaluated with Root Mean Square deviation analysis using Geomagic Control X. Statistical analysis were performed with a significance of $p<0.05$.

Results:

Primescan showed significantly greater depth of Reading than both Trios scanners, particularly in the 0.25mm gap, performing a mean depth of 1.23mm compared to 0.61mm for Trios 6 and 0.38 mm for Trios 4. Nonetheless, scanners performance improved with the increase of the gap from 0.25mm to 0.5mm. However, Trios scanners demonstrated lower RMS values than Primescan, these lower values were associated with reduced subgingival scanner penetration and readings. Suggesting that RMS alone may not adequately represent scanner performance mostly in subgingival areas. Horizontal preparation also exhibited greater scanning difficulty than the vertical preparation, with higher RMS values and lower reading depths.

Conclusion:

Scanner performance in subgingival area is affected by many factors, mostly gingival sulcus width and preparation geometry. Primescan demonstrated superior depth of reading, whereas Trios scanners showed lower RMS values. The findings suggest that scanner performance should be assessed by considering accuracy and data acquisition.

Keywords:

Intraoral Scanners, Digital Impression, Subgingival Margin, Accuracy

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Abbreviation List

AI – Artificial Intelligence
AW – Apical Width
CAD – Computer-Aided Design
CAD/CAM – Computer-Aided Design / Computer-Aided Manufacturing
CI – Confidence Interval
CV – Coefficient of Variation
CW – Coronal Width
DP – Disto-Palatal
DV – Disto-Vestibular
GDPR – General Data Protection Regulation
ISO – International Organization for Standardization
IOS – Intraoral Scanner
IOSs – Intraoral Scanners
MP – Mesio-Palatal
MV – Mesio-Vestibular
P – Palatal
ROI – Region of Interest
RMS – Root Mean Square
SD – Standard Deviation
SPSS – Statistical Package for the Social Sciences
STL – Standard Tessellation Language
TS – Test Statistic
V – Vestibular
3D – Three-Dimensional
µm – Micrometre

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Introduction

1. Introduction

1.1 Technological Advances in Dentistry

Over the last decade, dentistry has undergone significant changes by technological innovation and the development of new restorative materials. These changes have improved both functional and aesthetics of dental treatments. One of the most important developments in this transition has been the apparition and evolution of intraoral scanners (IOSs), changing the way diagnoses and planning of necessary treatment are made. Although early digital systems appeared several decades ago, their common adoption only occurred after marked improvements in hardware and software performance. With this evolution also appeared a high demand for better accuracy in impression methods and prosthetic treatment.(1–4)

An important milestone in this process was the introduction of IOSs in the 1980s, which initiated a fully digital workflow. Since it became possible to reduce failures when used conventional impression materials and techniques that also depended on the operator's experience.(2,5) But it was only in the 2000s that intraoral scanners became globally available on the market.(2) Early IOSs used optical triangulation and needed sometimes the use of powder like titanium dioxide to coat the teeth for better light and capture. (2–4)

Initially IOSs were mostly used in fixed prosthodontics, since IOSs progressively expanded their use to many dental fields, such as removable prosthetics, orthodontics, and implant planning, reflecting how versatile this technology is and how useful it could be.(1,5) Currently, every part of a prosthetic rehabilitation can be performed digitally, from impression taking to obtaining the final restoration.(6)

This successful expansion of IOSs in several dental specialties demonstrates not only the continuous adaptation of digital tools to the demands of dental practice, but also the consolidation of an irreversible trend towards the digitization of workflows, representing one of the most impactful advances in contemporary dentistry.(1,6)

Another important advantage part of IOSs is the ability to generate accurate three-dimensional representations of oral structures. These digital models are a lot more useful and simpler for a more efficiently workflow, than conventional stone casts. In addition, digital models stored facilitate long-term data management and simplify future treatments. (2–4)

Although further development is still needed, digital technology continues to gain relevance due to their versatility, efficiency and growing clinical use.(2)

1.2 Evolution of Impressions Techniques

1.2.1 Conventional vs. Digital Impressions

Conventional impressions techniques have always been a gold standard in dental practice due to elastomeric materials, such as addition silicones or polyethers, representing the standard approach for capturing dental and gingival structures in restorative dentistry. (3,7,8) Regardless of the technique used, capturing accurately the preparation margin is essential for a successful restoration with adequate marginal adaptation. The quality of the anatomy captured directly influences the exchange with the dental laboratory and consequently will interfere with the final prosthesis. (7,8)

The rheological properties from the conventional materials, gave the advantage of reaching deeper into the gingival sulcus, being able to capture even deeper details. The use of light-body materials in combination with more viscous impression materials improved even more the capture of subgingival details. Demonstrating the important characteristics of those impression, through the ability of elastomeric impression materials registering deeper tooth preparation margins and more apical dental anatomy.(6–8)

Conventional impression techniques have a better ability to reproduce oral structures with a greater level of detail, this contributed to their commonly clinical use. Despite their proven effectiveness, several limitations have motivated the clinical search for alternative approaches improving the growth of the adoption of digital technologies. (6)

Digital dentistry development increased the number of studies that focus on comparing digital and analog impression methods. This development has provided clinicians with new possibilities for capturing oral structures and integrating digital workflows into daily practice. Consequently, IOSs have been evaluated in progressively more demanding and complex clinical situations to understand their ability to maintain accuracy under different conditions.(1,5,8,9)

Rather than completely replacing older techniques, new digital impressions have gradually become an additional option available to clinicians. Conventional methods are still scientifically supported and successful to use in many clinical situations. However, digital workflows offer an efficiency and versatility greater explaining their implementation in modern dentistry. (1–3,9)

Continuous technological development has significantly improved the performance, current software can now even include real-time error detection. Modern systems may incorporate technologies such as confocal imaging, structured light projection, and advanced optical sensors to facilitate the capture of complex oral geometries. Different manufacturers employ distinct optical principles to acquire digital data. For instance, Dentsply Sirona ®(Charlotte, USA) transitioned from active triangulation technology in the Omnicam scanner to confocal technology in the Primescan scanner. Confocal technology is based on projecting light beams, that record only points in focus, resulting in high-resolution images. Through these technological improvements, current intraoral scanners can produce highly detailed digital models that support a wide range of restorative and diagnostic procedures. (1,3,8)

Both Primescan and Trios 4 3Shape ® (Copenhague, Denmark) have been highlighted in scientific studies, showing great promise, and are widely used in dental practice, due to their high precision and consistent integration with CAD/CAM (Computer-Aided Design/Computer-Aided Manufacturing) systems. Borbola et al. (2024) demonstrate a low mean deviation for the Trios 4 and high truenness and precision of the Primescan. Similarly, in Vag et al. (2023) report that the Primescan also has a low mean deviation, below 40 µm. (1,10)

1.2.2 Digital Impression in Different Dental Fields

Intraoral scanners are currently applied in several dental specialties, including removable prosthodontics, orthodontics, and implant dentistry, becoming an important component of modern digital workflows. In removable prosthodontics, IOSs can be used to record edentulous and partially edentulous arches, providing a digital alternative to conventional impression procedures. Digital workflows may improve communication between clinicians and dental laboratories while simplifying some stages involved in prosthesis fabrication. (11)

In orthodontics, digital impressions are widely used for diagnosis, treatment planning and long-term follow-up. The digital models obtained through intraoral scanning can support the fabrication of aligners, retainers, and other orthodontic appliances. Additionally, many orthodontics patient are young patient, and digital scanning can be more comfortable for them, since they can be less used to dental treatment like adult patient. Furthermore, digital records facilitate treatment monitoring and allow easier storage and retrieval of patient information.(4)

Implant dentistry has also benefited from the development of digital impression systems. Through intraoral scanning, clinicians can record the implant position with the surrounding soft tissues and adjacent structures, contributing to a more efficient digital workflow. This approach also improve communication with the dental laboratory. (1,3)

Despite their broad range of applications, fixed prosthodontics remains the area where it all started and intraoral scanners are most used. As a result, digital impressions have become an increasingly daily approach for the fabrication of indirect restorations and prosthetic rehabilitations.(1,3)

1.2.3 Benefits of Digital Impressions

The growing implementation of digital technologies has changed many aspects of dental practice. By eliminating several intermediate steps, digital impressions can simplify treatment procedures and contribute to a less step and quicker workflow. In addition, the absence of impression materials removes potential sources of distortion that could occur during mixing, setting, disinfection or model fabrication. (3,5,6)

Patient acceptance of a greater modern solution has also contributed to the increasing popularity of digital impressions. Conventional techniques can be uncomfortable for some patients, particularly those with a strong gag reflex or anxiety related to impression materials. In contrast, IOSs are generally perceived as a less uncomfortable procedure and can improve the overall patient experience. The shorter clinical time mostly associated with digital workflows is a daily advantage in clinical situation and is more attractive also to patient. (3,5,6)

The benefits of digital impressions extend beyond the clinical appointment itself. Once acquired, digital records can be transferred directly to the dental laboratory without the need for physical transportation. As mentioned it is a greater communication between clinicians and technicians and this allows a faster laboratory work. Furthermore, digital files can be archived electronically and retrieved whenever necessary, making future access if necessary for another treatment easier. (6)

Another important aspect is the compatibility of digital impressions with contemporary CAD/CAM systems. The direct integration between scanning, design and manufacturing technologies allows restorations to be planned and produced within a fully digital environment. (3,5,6)

Digital impressions have become an important component of modern dentistry, and their application continues to expand as technology improves. Nevertheless, despite the numerous advantages already demonstrated, further improvements are still being investigated in order to optimize the performance and clinical use of these new technology. (3,5,6)

1.2.4 Limitations of Digital Impressions

Although digital impressions have become increasingly popular in modern dentistry, several limitations still need to be considered. The performance of an IOS is influenced by a combination of technological, clinical and operator factors. (1,3,5,10)

One of the most frequently reported difficulty in the literature is to capture areas with limited optical access. Deep subgingival margins, narrow cervical regions and sulcus, present restricted optical access, making it difficult to acquire sufficient information, because the scanner requires a direct path for light projection. In such situations, the quality of the digital impression may be influenced not only by the scanner itself but also by the design of the tooth preparation and the visibility of the preparation margin. Clinical conditions inside the oral cavity may also interfere with the scanning process, saliva, blood, and soft tissue movement can affect image acquisition and make it more difficult to obtain a complete digital impression. For this reason, adequate isolation and tissue management remain important factors when performing digital impressions, especially in cases involving deep subgingival margins. (5,6,10,12)

Additionally, the learning process associated with the use of digital technologies should be considered. Although intraoral scanners are becoming easier to use, operator experience continues to play an important role in the quality of the final scan. Insufficient training, incorrect scanning strategies or inadequate handling of the scanner may result in missing data, image distortions or the need for repeated scans. (1,3,10)

Economic factors may also limit the adoption of digital workflows. The accessibility, and economics of purchasing a scanner remains a significant obstacle. To further elaborate, the cost of IOSs may restrain several small clinics, particularly in the smaller communities, from acquiring this technology. We must consider that purchasing an intraoral scanner is not enough, the scanner requires a software subscription, maintenance, and appropriate training to be used effectively. Many clinicians consider that these costs, have also a long-term benefit associated with digital workflows that could justify the investment.(13)

Despite these limitations, technological advances have continuously improved the abilities of modern intraoral scanners. As research and technological development continue, many of the current limitations are expected to become less significant in the future.

1.3 Clinical Factors and Digital Impressions

1.3.1 Geometry and Tooth Preparation

The design of the tooth preparation plays a fundamental role in fixed prosthodontics. The geometry of the prepared tooth directly influences the ability of intraoral scanners to capture complete and accurate digital data, ultimately affecting the quality of the final restoration. Tooth preparation with more complex morphology can significantly compromise the capture of the oral cavity and the reliability of the impressions. (5–7)

According to the Glossary of Dental Prosthesis Terms, the "finish line" or "margin" of an abutment is defined as "the junction of the prepared and unprepared tooth structure with the margin of a restorative material."(7,8)

The shape, angle, and location of the finish line are crucial clinical factors to consider during tooth preparation, as they can affect the scanner's ability to capture fine anatomical details and, consequently, the success of the restoration. Son & Lee (2021) observed that the location of the finish line also impacts the trueness and precision of digital impressions.(8) Therefore, preparation planning should take into account not only biomechanical and aesthetic aspects but also the optical and scanning limitations of digital systems, as the oral anatomy can affect light access and dispersion within the IOSs. (6,14)

In contrast, preparations presenting smooth surfaces, rounded transitions and clearly defined margins generally facilitate data acquisition, improving scan quality and reducing the need for digital corrections during post-processing.

Beyond geometry, the finish line location is equally important. (5–7) Monaco et al. (2024) reported that the ability of IOSs to record preparation margins decreases as the finish line becomes deeper within the gingival sulcus, highlighting the importance of margin location during treatment planning. (5)

1.3.2 Different Locations of Finishing Lines

As previously mentioned, according to the Glossary of Prosthodontic Terms, the finish line also referred to as the cervical margin, represents the transition between the prepared and unprepared tooth structure where the final restoration will meet the tooth surface. The definition of this line is crucial for both the mechanical and biological success of the prosthesis in the long term, particularly when associated with digital impressions, as it has a direct impact on the quality of data acquisition. (4–7)

In the literature, various finish line locations have been described depending on the prosthetics purpose.(12) The locations of finish lines are commonly classified into three categories. Supragingival margin, are located above the gingival tissues, which is the most recommended for periodontal health and scanner accessibility. Equigingival margin are positioned close to the gum line, which begins to present a moderate scanning challenge. Subgingival margin located within the gingival sulcus, often required in aesthetic areas, this margin requires greater care and precision from the clinician when being used. (5,6,8)

Several studies in the literature explains that IOSs are more accurate when detecting supragingival margins, being easier to isolate and reducing interference from saliva, bleeding, and soft tissues. Conversely, as the margin extends deeper into the sulcus, the difficulty of scanning the margin accurately increases, and it becomes harder to identify the surface beyond the margin. (5–8,12)

1.3.3 Challenges of Subgingival Margin

Subgingival finish lines are frequently used when aesthetic demands are high, particularly in the anterior region. By placing the restoration margin inside the gingival sulcus, clinicians can better hide the transition between the restoration and the natural tooth, improving the final aesthetic outcome. However, this approach also creates additional challenges, especially when digital impressions are used. (5,6,8)

The main difficulty lies in the limited optical visualization of the margin within the gingival tissue. Soft tissues may cover the finish line of the abutment becoming an obstacle for the scanner to capture it accurately. This limitation tends to be more significant when the margin goes deeper into the gingival sulcus.(6,7) For an IOS to read the margin within the gingival sulcus the presence of adjacent teeth, which may limit the space available to capture specific anatomical details may also be an obstacle to an accurate and precise capture of the margins.(6)

To overcome these limitations, adequate soft tissue management is essential. Different gingival displacement techniques have been proposed to expose the finish line and improve scanner access to the preparation margin. Several studies have reported that proper gingival retraction can significantly improve the visibility of subgingival areas and facilitate data acquisition during digital impressions. (5,15,16)

However, the literature reveals that the correct extent of the margin in the gingival sulcus should not exceed 0.5 mm to 1 mm. If this depth is not respected and a margin is positioned deeper than 1 mm in the sulcus, it becomes harmful potentially damaging with time the epithelial attachment tissue, as well as significantly increasing gingival inflammation. (12)

The characteristics of the scanner itself may also influence the ability to capture subgingival areas. Different IOSs systems use distinct optical technologies and image processing algorithms, which may affect their performance in challenging clinical situations. Recent studies have shown that scanner performance may vary considerably when attempting to capture preparation margins located within the gingival sulcus.(1,9)

1.3.4 Gingival Retraction and Techniques

When a preparation margin is located below the gingival margin, soft tissue displacement is often required before making an impression. Gingival retraction aims to temporarily move the gingival tissues away from the tooth surface, creating sufficient space for impression materials or intraoral scanners to record the finish line accurately. Proper tissue displacement is therefore an important step in obtaining complete and reliable digital impressions. (16–18)

Several gingival retraction techniques are explained in the literature. These methods are classified as mechanical, surgical, chemical, and laser-assisted techniques. The choice of which one use is made depending on the clinical case, and the clinician's preference. (16–18)

Mechanical gingival with cords is one of the techniques most used in daily clinical cases, because of their accessibility and effectiveness. In many cases, they are used together with hemostatic agents to control bleeding, since it is a more traumatic retraction. However, it is important to understand this technique because if not done properly it can cause discomfort and traumatize the soft tissues. (16–19)

Cordless systems, such as pastes or injectable materials, offer a less invasive mechanical method chemically assisted reducing the patient discomfort while still providing a great retraction.(17,19) Laser-assisted techniques have also been a great alternative to quickly retract the soft tissues, still controlling bleeding although it is not commonly used because of the requirement for expensive equipment and the need for training.(16,18)

Chemicals agents are frequently used in complement of a mechanical technique by improving hemostasis and improving tissue visibility, but it should be done with caution, if done excessively it may irritate the gingiva. (16,17,19)

1.3.5 Best Gingival Retraction for Digital Impressions

The success of a digital impression when there are subgingival margins is closely related to how well the gingiva are moved out of the way. Even the best intraoral scanners can struggle to take an impression if the soft tissues cover the area to be scanned. Therefore, adequate retraction is essential before taking digital impressions. Studies have shown that when the preparation margin is exposed properly scanners can give higher accurate results.

The selection of the most appropriate retraction technique should be based on the clinical situation. Factors such as gingival biotype, sulcus depth and margin location may influence the amount of tissue displacement required. In cases involving deeper subgingival margins, mechanical cord retraction continues to be considered one of the most predictable approaches because it provides effective lateral and vertical displacement of the gingival tissues, combined with a mild hemostatic agent, so that the bleeding does not compromise the scanning process.(16–19) The combination of cord and retraction paste can also occasionally be used to optimize exposure without increasing the risk of tissue damage. In a vertical preparation it is also common to use the own provisionary crown with retraction paste for a mechanical retraction. (16,19)

In contrast because of the possible irritation of soft tissue and interference with the optical capture of the scanners, chemical methods alone could not be considered for a primary approach in this situation using IOS, they are a better fit to complement the mechanical method.(16,17,19)

Overall, the current evidence suggests that there is no single technique for every clinical case. Mechanical cord retraction is still the reliable method when a lot of margin exposure is needed. Cordless systems may be better, for patient comfort and ease of use. The dentist should choose the approach based on each individual case. (16–19)

1.4 The Accuracy of Intra Oral Scanners

1.4.1 Trueness and Precision in Impressions

The development of scanners has led to a great interest in analyzing how accurate digital impressions are. In prosthetic dentistry accuracy is very important because it affects the fit and quality of the final restoration. Several studies have investigated the ability of IOSs to reproduce oral structures faithfully and consistently.(3,4,10,14)

According to the International Organization for Standardization (ISO), accuracy is composed with two different parameters: trueness and precision. Trueness refers to how close a digital model is to the real object being scanned, while precision describes the ability of a scanner to reproduce similar results when multiple scans are performed under the same conditions. Both parameters are important when evaluating the performance of digital impression systems. (14)

The accuracy of a scanner can vary depending on several clinical and technical factors. Lighting conditions, preparation design, scanner technology, saliva, blood, and the position of the finish line may all influence the result. For this reason, the quality of an impression does not depend exclusively on the scanner itself but also on the clinical environment in which the scan is performed.(5,12,14)

Son Y.T. et al. (2022) highlighted that when gingival retraction is used in conjunction with deeper margins, digital impression precision improves.(12)Nevertheless, the literature indicates that more specific studies are still needed to understand the impact of various finish line locations on IOSs accuracy.(5)

From a clinical perspective, both trueness and precision of IOSs are important because inaccuracies may affect how great the marginal and internal adaptation of restorations will be. Even tough modern IOSs generally demonstrate clinically acceptable performance, maintaining optimal scanning conditions remains essential to achieve predictable results. The literatures have shown that IOSs accuracy greater than 100 μm may compromise marginal and internal fit of the future restorations.(12)

1.4.2 Periodontal Health on Scanning Accuracy

The condition of the surrounding periodontal tissues may also influence the quality of digital impressions. Factors such as gingival biotype, tissue health and the presence of inflammation can affect the visibility of the preparation margin and consequently the performance of intraoral scanners. (5,8,12)

Gingival biotypes are usually described as thin or thick. Thin gingival tissues tend to be more susceptible to recession and may present greater difficulty when margins are positioned subgingivally. In contrast, thicker tissues are usually more stable and may facilitate the exposure of preparation margins during the impression procedures. (5,12)

Periodontal health is also as important for successful digital impressions. Inflammation, bleeding, may interfere and influence with light reflection and reduce the quality of the captured data. These factors become particularly relevant when scanning subgingival margins, where a clear visualization of the finish line is essential for obtaining an accurate digital model. Adequate periodontal health, together with appropriate gingival retraction, can improve margin visibility and contribute to more reliable digital impressions. (12,16–19)

In summary, both biotype as well as periodontal health can directly influence the digital impression. Therefore, the literature highlights the importance of thorough soft tissue management prior to scanning.

1.5 Artificial Intelligence in Intraoral Scanning

Artificial intelligence (AI) has become increasingly present in digital dentistry and is gradually being incorporated into intraoral scanning systems. Its main objective is to assist the clinician during image acquisition and processing, improving the quality of digital impressions and reducing the possibility of errors. Through advanced algorithms, AI can support the identification of dental structures, soft tissues, and preparation margins, helping to create more complete digital models.(1,3,10,20)

Recent studies have suggested that AI may contribute to a more efficient recognition of finish lines, including margins located in areas that are difficult to visualize. Róth et al. reported that AI-assisted scanning systems could improve margin detection and enhancing the overall quality of digital impressions. These developments may be particularly relevant in situations where subgingival margins or complex anatomical structures are present. Another benefit of AI is that it can make digital impressions more consistent. When a clinician takes an impression, the quality can change depending on their experience how they scan and if they can spot areas that are not clear. AI systems can help by finding data showing areas that need to be rescanned and guiding the clinician during the scan. (20)

In fixed prosthodontics, accurate detection of the preparation margin is essential for the final restoration. AI may also contribute with post-processing the data by smoothing surfaces, aligning scans, and facilitating the creation of digital models that are ready for CAD/CAM workflows improving efficiency. (20,21)

AI is not a substitute for proper clinical practice. Factors such as tissue management, gingival retraction and adequate scanning technique remain fundamental for obtaining digital impressions. Nevertheless, current evidence suggests that artificial intelligence will continue to play an important role in digital dentistry and may contribute to further improvements, in the accuracy and predictability of intraoral scanning systems. It´s likely that AI will become an essential part of digital workflows in dentistry.(20,21)

1.6 Ethical and Data Protection in Digital Dentistry

Digital dentistry is relying increasingly on high volumes of clinical data from intraoral scanners, this means a lot of patient data is being collected and stored with AI systems, and CAD/CAM workflows. As Brinz et al. (2025) pointed out, these datasets often contain highly personal information, making ethical considerations and data preservation essential in today's dental practice. (21)

As digital workflows continue to expand, dental professionals have a more important responsibility regarding the management of patient's information. The use of AI may require access to large datasets for training and optimization, making it essential to ensure that patient information is handled securely and responsibly. Ethical use of these technologies should always prioritize patient safety, privacy, and transparency. (21)

Within the European Union, the processing of digital health information must comply with the General Data Protection Regulation (GDPR). These regulations establish rules regarding data collection, storage and sharing, ensuring that personal information is used only for legitimate clinical or research purposes. Furthermore, newly emerging privacy techniques such as federated learning which is an AI technique to share models without transferring personal dental data, provide an essential role in protecting patient information while allowing technological advancement.(21)

Finally, the success of digital dentistry depends not only on technological improvement but also on maintaining ethical standards and public trust. Patients must feel confident that their personal information is protected and that digital technologies are being used responsibly. (21)

1.7 Depth of Digital Reading in The Gingival Sulcus

The depth that can be captured with IOSs within the gingival sulcus has been extensively studied due to its direct influence on the accuracy of reproducing preparation margins and, consequently, the success of future restorations. As previously mentioned, the difficulty in capturing margins located deeper within the gingival sulcus remains one of the main challenges of digital impression. (6,8)

Several studies have investigated how deeply intraoral scanners can record structures within the gingival sulcus. Monaco et al. (2024) reported that all evaluated scanners were capable of capturing information at depths approaching 1 mm, with some differences. The authors also noted that the quality of the captured data tended to decrease as the depth increased, which may be related to the reduced ability of light to reach deeper regions of the sulcus.(8)

Similar findings were reported by Sorrentino et al. (2024), who demonstrated that intraoral scanners were capable of capturing subgingival data approaching 1 mm on buccal surfaces. In addition, Zarone et al. (2025) observed that margins positioned deeper than 1 mm below the gingival margin were associated with greater deviations and lower scanning accuracy. These findings suggest that increasing subgingival depth may negatively affect the quality of digital impressions.(6,7)

Overall, the available evidence indicates that the depth of reading within the gingival sulcus remains an important factor when performing digital impressions. Although modern scanners have demonstrated promising results, adequate gingival management and appropriate preparation design continue to be essential for obtaining predictable outcomes in cases involving subgingival margins. (6–8,14)

Table 1 - Summary of the main characteristics of IOSs evaluated in the present study.Clique ou toque aqui para inserir o texto.

Scanner	Acquisition Technology	Software	Advantages	Limitations
Primescan	High-frequency, structured light	Connect software	Literature reported high trueness, and the ability to capture more complex geometries and subgingival areas.	Accuracy decreases in limited optical access
Trios 4	Confocal technology that only captures with focus and sufficient optical quality	3Shape Unite	High trueness and precision, efficient workflow integration, user friendly interface.	Reduced ability to capture deep subgingival area due to optical access compromised
Trios 6	Advanced confocal technology	3Shape Unite	High trueness and precision, efficient workflow integration, user friendly interface.	Reduced ability to capture deep subgingival area due to optical access compromised

Table 1 summarizes the main technological characteristics, software, advantages, and limitations of the intraoral scanners evaluated in the present study. Although, since limited scientific evidence is currently available specifically for the Trios 6, information related to this system was partially retrieved from studies investigating previous generations of the Trios platform, which share similar optical technology and software interface.

Objectives

2. Objectives

The present in vitro study was designed to evaluate the ability of intraoral scanners to identify and reproduce subgingival preparation margins under standardized gingival sulcus conditions. Particular attention was given to the capacity of the scanners to capture anatomical structures located within the gingival sulcus, an area where optical access is naturally limited and image acquisition may be more challenging.

Therefore, it mostly aims to evaluate and compare the depth of reading and geometric accuracy of three intraoral scanners (Primescan, Trios 4, Trios 6) in subgingival margin with different preparation geometries and gingival sulcus width. This research focuses on determining the reliability and technical limitations of the intraoral scanning system by analyzing digital impressions.

Additionally, the study aimed to investigate the relation between depth of reading and Root Mean Square values, in order to determine whether lower geometric deviations are associated with a more complete subgingival capture.

The findings of this study may contribute to a better understanding of the current capabilities and limitations of intraoral scanners when used in clinically demanding situations. Furthermore, they may assist clinicians in selecting appropriate digital workflows and planning restoration margins in cases involving subgingival preparations.

Null hypothesis:

H_{01}: No statistically significant differences exist in the depth of reading between among the tested scanners.

H_{02}: Gingival sulcus width does not significantly influence the depth of reading from scanners.

H_{03}: Tooth preparation geometry does not significantly influence the depth of reading.

H_{04}: No statistically significant differences exist in geometric accuracy among the different intraoral scanners or tested experimental conditions.

H_{05}: No statistically significant correlation between depth of reading and the Root Mean Square values.

Materials and Methods

3. Materials and Methods

3.1 Study Design

This experimental in vitro study was conducted to assess the ability of different IOSs to capture subgingival structures under controlled gingival sulcus conditions. An in vitro design was selected in order to minimize the influence of clinical variables that could affect scanning performance.

Three parameters of the gingival sulcus were used: apical width (AW): distance between the abutment surface and gingival tissue at a distance of 0.15 mm from the base of the gingival sulcus. Coronal width (CW): distance between the abutment surface and gingival tissue at the most coronal point of the gingival sulcus. Depth of the gingival sulcus (D): distance between the most coronal point and the bottom of the gingival sulcus.

Three IOSs were tested: Trios 4, Trios 6, and Primescan, as these scanners are commonly used in clinical cases. The scanning process was conducted using the most up-to-date acquisition software program available, also considering resolution with high-definition mode, depth, and angulation.

3.2 Models Design and Fabrication

Both models were virtually designed with a standardized gingival sulcus were designed from a . In both models, the gingival sulcus had an apical width (AW) of 0.250 mm and a coronal width (CW) of 0.600 mm. The depth of the margin was set for both models, H1 and H2, at 2 mm for a more complex case study. The difference is that for each one, we made 2 models one with a gingival gap of 0.25 mm and one with 0.5 mm gap.

An STL file of a model containing prepared teeth was initially obtained and subsequently modified to design a gingival sulcus matching the predefined dimensions. The gingival sulcus was digitally created using a dedicated dental CAD software program (Model Creator, exocad DentalCAD 2.4; exocad, Darmstadt, Germany). The models were manufactured using a Phrozen Sonic Mini 8K resin 3D printer (Phrozen, Taiwan), recognized for its high-precision printing capability and 22 μm resolution, a gray resin (Phrozen Aqua Gray 8K resin; Phrozen, Taiwan) was used for all printed models. Models were printed and post-processed by the same operator.

Table 2 - Physical and chemical properties of the resin used (Phrozen Aqua Gray 8K Resin), according to the manufacturer's safety data sheet

Property	Value
Appearance and colour	Gray viscous liquid
Odor	Typical acrylate
Specific gravity	1.18 g/cm³ at 25 °C / 77 °F
Viscosity	320–350 cPs
Flash point	> 110 °C / 230 °F
Solubility in water	Insoluble
Solubility in organic solvents	Soluble
Electrostatic discharge	Safe
Electric conductivity	Dielectric

The canine preparation was designed according to the vertical preparation concept (VertiPrep), with infra-gingival margins all around the preparation in order to simulate deep subgingival clinical conditions

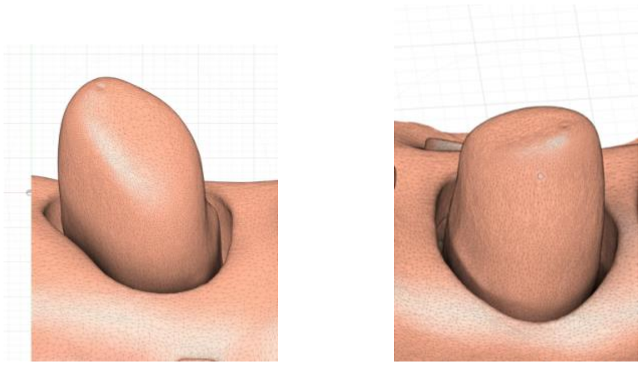


Figure 1 - Canine preparation with vertiprep and circumferential infragingival margins

The molar preparation was designed with a shoulder finish line. The vestibular margins were positioned infra-gingivally, while the palatal margins were positioned at equi-gingival and supra-gingival levels, allowing the evaluation of scanner performance under different marginal depth conditions.

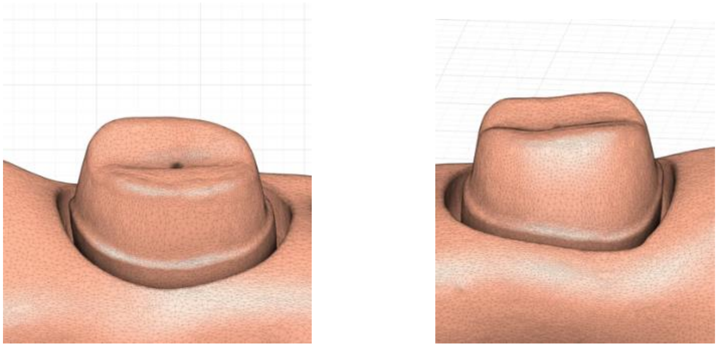


Figure 2 - Molar shoulder preparation with infragingival vestibular margins and equi/supra gingival palatal margins

3.3 Data Analysis

Both model for H1 and H2 were scanned 10 times using the three different intraoral scanners by the same operator, with the model in hand. The digital impressions were exported in STL format for subsequent analysis. 60 STL files were made in total and were used to evaluate scanner performance in capturing the gingival sulcus area, with particular attention to the representation of sulcus depth and subgingival regions.

The files generated by the IOSs, and the desktop scanner were imported into a software program (Geomagic Control X 2022; 3D Systems Inc, USA) to assess deviation in trueness. All linear measurements were recorded in millimeters (mm).

For each model (H1 and H2), the STL datasets were initially aligned and then superimposed using a Best-Fit Alignment procedure to ensure optimal matching between the scanned surfaces. The measured scan data was aligned to the reference coordinate system to ensure accurate spatial comparison. This alignment allowed the calculation of surface deviations across the entire geometry before specific regions were isolated.

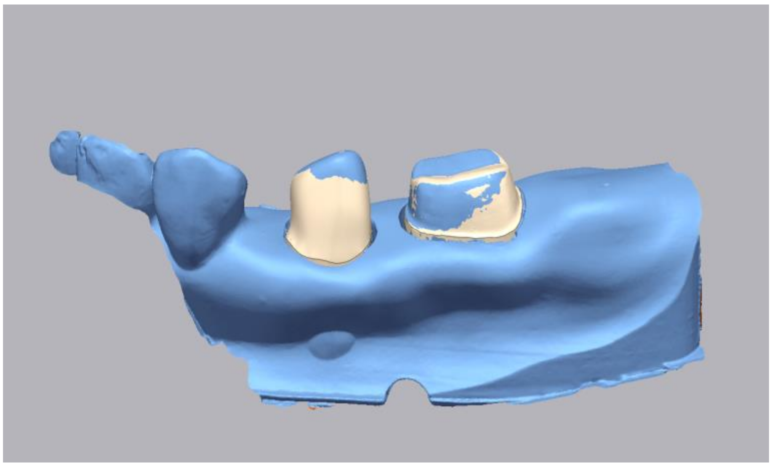


Figure 3 – Superimposition of the STL with the reference model after Best-Fit Alignment

Three-dimensional (3D) deviation analysis was performed using the 3D Compare function. To analyze specific anatomical and functional areas, the models were segmented into two primary Regions of Interest (ROI): Abutment: defined for both the canine and molar areas. Sub-gingival: defined as the area immediately below the gingival margin for both the canine and molar.

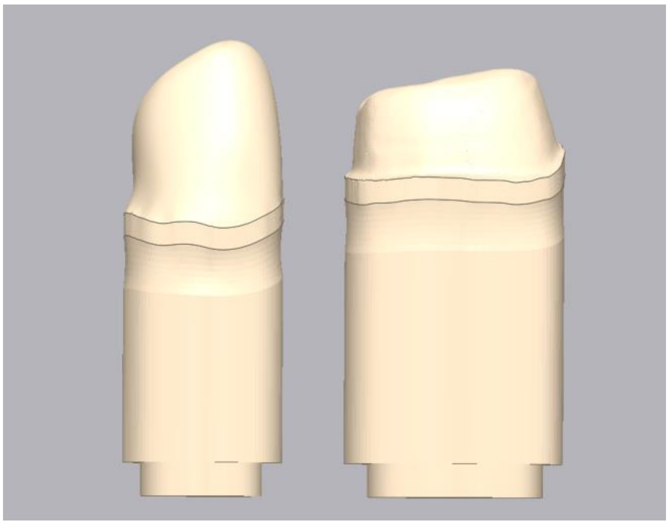


Figure 4 - Definition of the ROI used for the analysis, the abutment, and sub-gingival areas for both canine and molar preparation

This analysis generated color-coded maps to visualize discrepancies between the superimposed digital models. The color maps displayed deviations ranging from +0.3 mm to −0.3 mm, with a tolerance range of ±0.02 mm, allowing a detailed evaluation of clinically relevant differences, especially at the subgingival marginal area. The analysis focused on the marginal region, and comparisons were made between the two sulcus depths (H1 and H2) and among the three intraoral scanners to assess differences in scanning accuracy under standardized conditions.

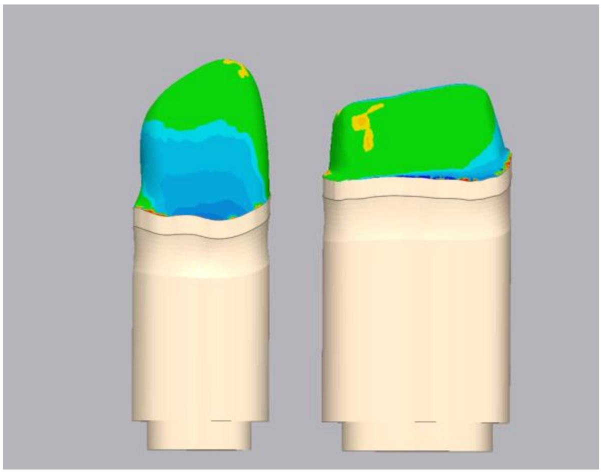


Figure 5 - Color-coded deviation maps of the abutment regions for the canine and molar preparation

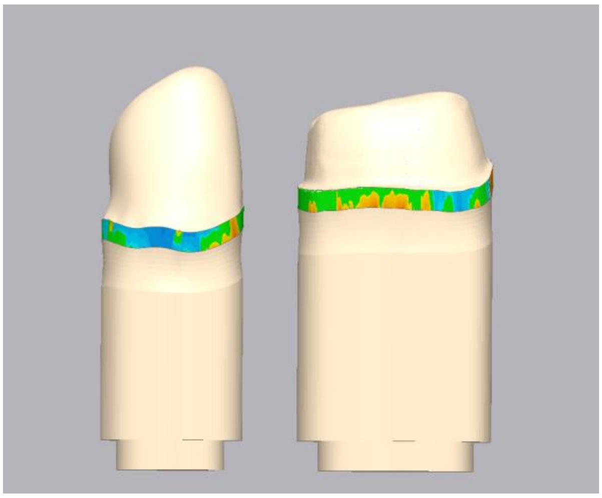


Figure 6 - Color-coded deviation maps of the sub-gingival regions for the canine and molar preparations

Additionally, linear measurements were performed using Fusion 360 (Autodesk Inc., USA) in order to evaluate the depth of digital reading in the gingival sulcus in all the STL files obtained. All measurements were recorded in millimeters (mm).

Three reference points were defined on both vestibular and palatal surfaces for both tooth preparations, corresponding to mesio-vestibular (MV), vestibular (V), disto-vestibular (DV), mesio-palatal (MP), palatal (P), and disto-palatal (DP). For each reference point, using the Cut Analysis tool a frontal plane section was chosen in order to expose the subgingival reading area and allow linear measurement of the readable depth.

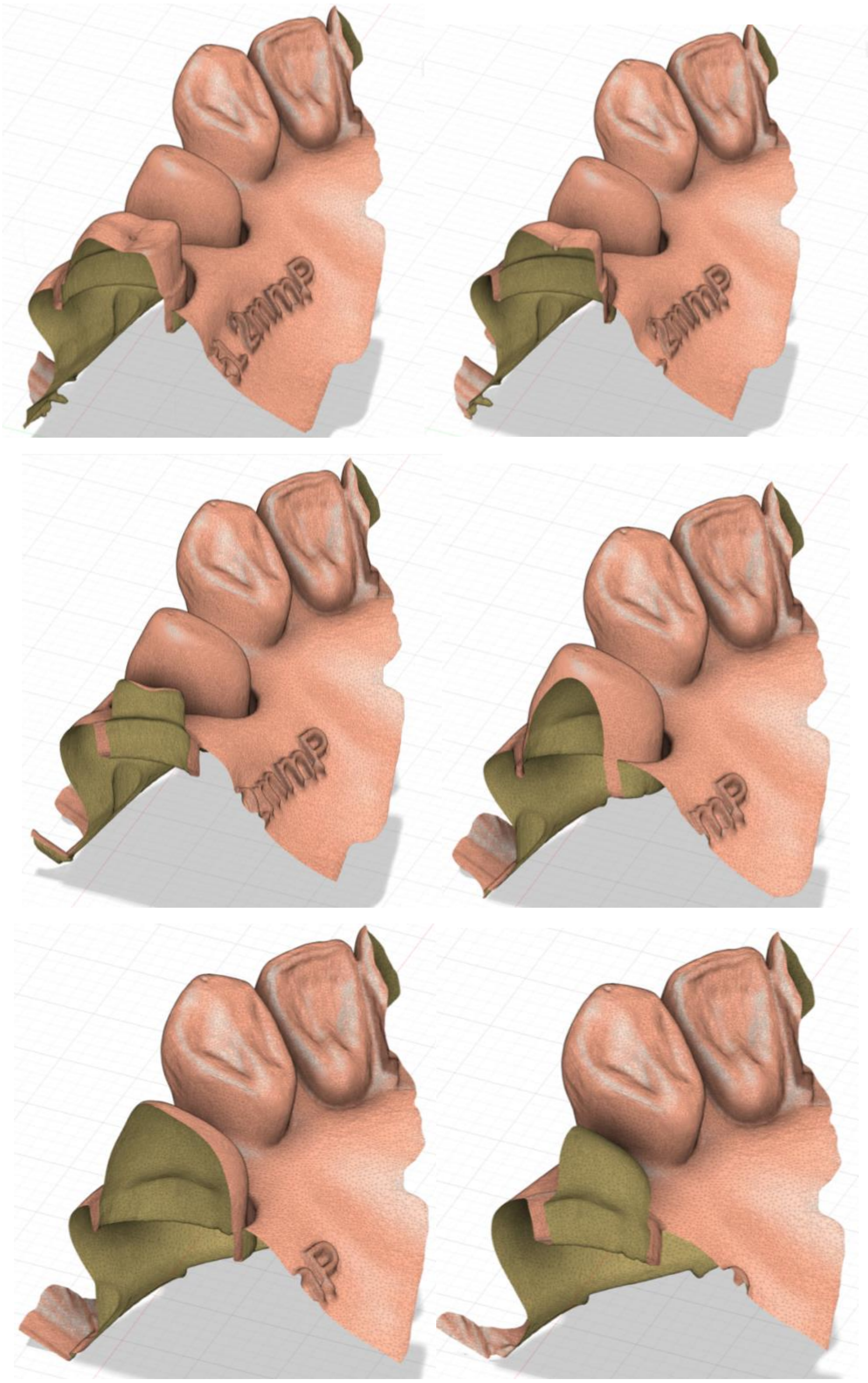


Figure 7 - Representation of all frontal sections created using the Cut Analysis tool for linear measurments

Measurements were taken in every reference point for every STL files using the measure tool, these measurements were made from the beginning of the sulcus to the deepest point reached by the intraoral scanner. This methodology allowed the assessment of the maximum readable depth achieved by each intraoral scanner, providing a quantitative evaluation of their ability to capture subgingival areas.

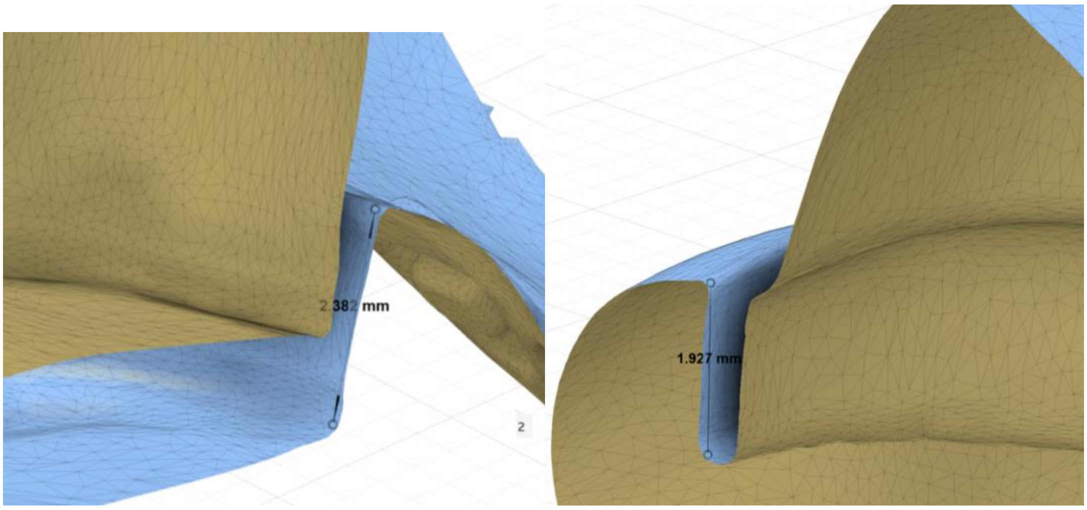


Figure 8 - Example of measurement made using the measure tool for each reference point

3.4 Statistics

Descriptive statistics, including mean, median, standard deviation (SD), global minimum, and maximum values, were calculated. These statistics were used to summarize the measurements obtained from the different intraoral scanners and gingival sulcus depths.

A 3D comparison was executed to calculate the surface deviations between the reference and measured data within the defined ROIs. The primary metric for accuracy was the Root Mean Square (RMS) error, which provides an aggregate measure of total deviation. Lower RMS values indicated better agreement between scans and higher accuracy. The calculation used for the RMS is as follows:

$$RMS = \sqrt{(1/n) \Sigma (x_{i,ref} - x_{i,meas})^2}$$

Additional statistical parameters recorded for each ROI included minimum and maximum deviations to identify extreme outliers, average deviation to determine the overall directional shift (positive or negative), standard deviation and variance to assess the precision and distribution of the data points, and In-Tolerance (%) corresponding to the percentage of the surface area falling within the specified tolerance range.

To compare the performance of the intraoral scanners (Trios 4, Trios 6, and Primescan) and the two-gap width (0.25 mm and 0.5 mm), a linear model was used, with root mean square (RMS) as the dependent variable to assess scanning accuracy, and scanner type and sulcus depth as the independent variables.

When statistically significant differences were detected, a post-hoc Tukey test was performed to identify differences between individual groups. Precision was defined as the degree of variance within groups of scans, whereas trueness was defined as the deviation between the digital impressions and the reference model.

The level of statistical significance was set at $p < 0.05$. All analyses were conducted using SPSS Statistics 29.0 (IBM Corp., Armonk, NY, USA).

Results

4. Results

4.1 Linear Measurements Analysis

To evaluate the effect of the IOSs type, gap, depth (0.25 mm vs 0.5 mm) and their interaction on linear measurements, a non-parametric rank-based factorial model was applied due to the violation of parametric ANOVA assumptions. Additionally, the Friedman test was utilized to compare the six different measurement locations (disto-buccal, buccal, mesio-buccal, disto-palatal, palatal, and mesio-palatal), while the Wilcoxon signed-rank test was employed to contrast measurements between the molar and canine teeth.

4.1.1 Molar Linear Measurements

Table 3 - Characterization of the linear measurements of the molar and global molar mean

Scanner	GAP	Descriptive Metrics	Molar – measurements						
			Disto - buccal	Buccal	Mesio - buccal	Disto – palatal	Palatal	Mesio-palatal	Global
Primescan	0.50 mm	$\bar{X}$±s	1,780 ± 0,024	2,240 ± 0,030	2,566 ± 0,029	2,045± 0,114	1,825 ± 0,063	2,523 ± 0,079	2,163 ± 0,010
		CV	1,35%	1,35%	1,12%	5,56%	3,44%	3,14%	0,46%
		CI 95%	[1,763 - 0,797]	[2,218 - 2,262]	[2,545 - 2,587]	[1,964 - 2,126]	[1,780 – 1,870]	[2,466 – 2,580]	[2,156 - 2,170]
	0.25 mm	$\bar{X}$±s	0,555 ± 0,136	0,638 ± 0,595	1,161 ± 0,969	1,349 ± 0,673	1,800 ± 0,569	2,507 ± 0,485	1,335 ± 0,373
		CV	24,44%	93,31%	83,48%	49,87%	31,63%	19,36%	27,94%
		CI 95%	[0,458 – 2,262]	[0,212 - 2,587]	[0,468 – 1,854]	[0,868 – 1,830]	[1,393 – 2,208]	[2,160 – 2,854]	[1,068 - 1,602]
Trios 4	0.50 mm	$\bar{X}$±s	1,688 ± 0,150	2,108 ± 0,168	2,486 ± 0,064	2,194 ± 0,255	1,754 ± 0,467	2,348 ± 0,551	2,096 ± 0,185
		CV	8,87%	7,98%	2,56%	11,61%	26,63%	23,47%	8,81%
		CI 95%	[1,581 – 1,795]	[0,988-2,228]	[2,400 – 2,532]	[2,012 – 2,376]	[1,420 – 20,88]	[1,954 – 2,742]	[1,954 2,229]
	0.25 mm	$\bar{X}$±s	0,373 ± 0,094	0,364 ± 0,041	0,690 ± 0,696	0,385 ± 0,072	0,357 ± 0,067	0,347 ± 0,062	0,419 ± 0,124
		CV	25,15%	11,30%	100,83%	18,70%	18,77%	17,82%	29,65%
		CI 95%	[0,306 – 0,440]	[0,335 – 0,393]	[0 192 – 1,188]	[0 333 – 0,437]	[0,309 – 0,405]	[0,303 – 0,391]	[0,330 - 0,508]
Trios 6	0.50 mm	$\bar{X}$±s	1,822 ± 0,911	2,269 ± 0,097	2,529 ± 0,095	2,058 ± 0,115	1,780 ± 0,065	2,378 ± 0,125	2,139 ± 0,043
		CV	5,00%	4,30%	3,77%	5,60%	3,67%	5,24%	2,02%
		CI 95%	[1,757 – 1,887]	[2,199 – 2,339]	[2,461 – 2,597]	[1,976 – 2,140]	[1,733 – 1,827]	[2,289 – 2,467]	[2,108 - 2,170]
	0.25 mm	$\bar{X}$±s	0,565 ± 0,161	0,580 ± 0,203	0,889 ± 0,285	0,411 ± 0,029	0,451 ± 0,065	0,489 ± 0,251	0,564 ± 0,066
		CV	28,48%	34,92%	32,07%	7,11%	14,31%	51,41%	11,64%
		CI 95%	[0,450 – 0,680]	[0,435 – 0,725]	[0,685 – 1,093]	[0,390 – 0,432]	[0,405 – 0,497]	[0,309 – 0,669]	[0,517 - 0,611]

$\bar{X}$±s – mean ± standard deviation; CV – coefficient of variation; CI 95% - confidence interval for the mean 95%

In the analysis of molar linear measurements, mean values were generally higher at the 0.50 mm gap than at the 0.25 mm gap, regardless of the intraoral scanner used. At the 0.5mm gap, all three scanners (Primescan, Trios 4, and Trios 6) demonstrated relatively similar global means. However, at the 0.25 mm gap, discrepancies were more marked: Primescan showed the highest global mean (1.335 ± 0.373 mm) whereas Trios 4 showed the lowest (0.419 ± 0.124 mm). Furthermore, the coefficient of variation (CV) indicated greater measurement stability at the 0.50 mm gap, particularly for Primescan and Trios 6, while the 0.25 mm gap was characterized by high dispersion and lower repeatability across several locations.

The factorial model on ranks for the molar (**Table 3**) confirmed a statistically significant effect of the scanner factor on the global mean and across all regions (p < 0.05) except for the disto-palatal site (p = 0.052).

Table 4 - Results of the factorial rank analysis: scanner and gap effects on molar measurements

Analysis	Molar – measurements						
	Disto - buccal	**Buccal**	**Mesio - buccal**	**Disto – palatal**	**Palatal**	**Mesio-palatal**	**Global**
Scanner Factor-TS (p)	12,638 (<0,001)	10,340 (<0,001)	3,633 (0,033)	3,132 (0,052)	29,781 (<0,001)	44,435 (<0,001)	19,923 (<0,001)
Scanner - Effect - η^2	0,319	0,277	0,119	----	0,524	0,622	0,425
GAP Factor - TS (p)	240,666 (<0,001)	160,011 (<0,001)	70,030 (<0,001)	205,626 (<0,001)	37,896 (<0,001)	42,617 (<0,001)	286,037 (<0,001)
GAP - Effect - η^2	0,817	0,748	0,565	0,792	0,412	0,441	0,841
Scanner*GAP - TS (p)	0,281 (0,756)	0,128 (0,880)	0,089 (0,915)	13,955 (<0,001)	23,876 (<0,001)	18,723 (<0,001)	3,249 (0,047)
Scanner*GAP - Effect - η^2	----	----	----	0,341	0,469	0,409	0,107
Bonferroni Post Hoc	Trios 4 from others	Trios 4 from others	Trios 4/ Primescan	------	Primescan from others	Primescan from others	Primescan from others

TS (p) - Test Statistic (p-value).

The factor analysis presented in Table 3 regarding the positions revealed a statistically significant effect of the scanner on most linear measurements of the molar, specifically in the disto-vestibular, vestibular, mesio-vestibular, palatal, and mesio-palatal regions, as well as in the overall mean. Only the disto-palatal region showed no statistical significance. The gap factor showed a statistically significant effect in all measurements analyzed, with particularly high effect sizes in the overall mean, the disto-vestibular, disto-palatal, and vestibular regions. These results indicate that the depth of the gap had a marked influence on the linear measurements of the molar. The scanner versus gap interaction was significant in the disto-palatal, palatal, mesio-palatal, and overall mean regions, suggesting that the effect of the gap was not uniform across scanners, particularly in the palatal areas. Post hoc tests indicated that the Trios 4 differed from the other scanners in the disto-vestibular and vestibular regions, while the Primescan differed from the others in the palatal, mesio-palatal, and overall mean regions.

4.1.2 Canine Linear Measurements

Table 5 - Characterization of canine linear measurements and overall canine mean

Scanner	GAP	Descriptive Metrics	Canine – measurements						
			Disto - buccal	**Buccal**	**Mesio - buccal**	**Disto – palatal**	**Palatal**	**Mesio-palatal**	**Global**
Primescan	0.50 mm	$\bar{X}$±s	1,844 ± 0,068	1,769 ± 0,038	2,759 ± 0,064	2,838 ± 0,164	2,409 ± 0,097	2,497 ± 0,223	2,353 ± 0,020
		CV	3,66%	2,17%	2,31%	5,78%	4,02%	8,95%	0,87%
		CI 95%	[1,796 – 1,892]	[1,742 – 1,796]	[2,713 – 2,805]	[2,721 – 2,955]	[2,340 – 2,478]	[2,337 – 2,657]	[2,338 – 2,367]
	0.25 mm	$\bar{X}$±s	1,664 ± 0,653	1,064 ± 0,599	1,547 ± 1,020	0,644 ± 0,317	0,342 ± 0,055	1,481 ± 1,178	1,124 ± 0,280
		CV	39,24%	56,31%	65,90%	49,25%	15,94%	79,53%	24,95%
		CI 95%	[1,197 – 2,131]	[0,635 – 1,493]	[0,818 – 2,276]	[0,417 – 0,871]	[0,303 – 0,381]	[0,638 – 2,324]	[0,923 – 1,324]

Trios 4	0.50 mm	$\bar{X}$±s	2,010 ± 0,179	1,637 ± 0,297	2,467 ± 0,277	2,714 ± 0,520	1,747 ± 0,879	1,636 ± 0,901	2,035 ± 0,364
		CV	8,90%	18,13%	11,24%	19,16%	50,32%	55,07%	17,90%
		CI 95%	[1,882 – 2,138]	[1,425 – 1,849]	[2,269 – 2,665]	[2,342 – 3,086]	[1,118 – 2,376]	[0,992 – 2,280]	[1,775 – 2,296]
	0.25 mm	$\bar{X}$±s	0,417 ± 0,230	0,294 ± 0,094	0,292 ± 0,120	0,336 ± 0,100	0,344 ± 0,046	0,315 ± 0,062	0,333 ± 0,059
		CV	55,23%	31,96%	41,18%	29,80%	13,23%	19,75%	17,69%
		CI 95%	[0,252 – 0,582]	[0,227 – 0,361]	[0,206 – 0,378]	[0,264 – 0,408]	[0,311 – 0,377]	[0,270 – 0,360]	[0,291 – 0,375]
Trios 6	0.50 mm	$\bar{X}$±s	1,977 ± 0,153	1,786 ± 0,072	2,700 ± 0,142	2,464 ± 0,948	1,973 ± 0,784	2,373 ± 0,048	2,212 ± 0,257
		CV	7,76%	4,04%	5,25%	38,49%	39,73%	2,01%	11,63%
		CI 95%	[1,867 – 2,087]	[1,734 – 1,838]	[2,599 – 2,801]	[1,786 – 3,142]	[1,412 – 2,534]	[2,339 – 2,407]	[2,028 – 2,396]
	0.25 mm	$\bar{X}$±s	0,837 ± 0,675	0,947 ± 0,515	0,790 ± 0,368	0,519 ± 0,216	0,408 ± 0,164	0,382 ± 0,133	0,647 ± 0,256
		CV	80,62%	54,36%	46,58%	41,70%	40,14%	34,77%	39,55%
		CI 95%	[0,354 – 1,320]	[0,579 – 1,315]	[0,527 – 1,063]	[0,364 – 0,674]	[0,291 – 0,525]	[0,287 – 0,477]	[0,464 – 0,830]

$\bar{X}$±s – mean ± standard deviation; CV – coefficient of variation; CI 95% - confidence interval for the mean 95%

Analysis of the linear measurements of the canine tooth revealed that the mean values were generally higher for the 0.50 mm gap compared to the 0.25 mm gap, regardless of the scanner used consistently with the molar findings. At the 0.50 mm gap, the Primescan had the highest overall mean (2.353±0.020 mm), followed by the Trios 6 and the Trios 4. At the 0.25 mm gap, the same result persisted with highest overall mean from primescan (1.124±0.280 mm), although with a marked reduction in mean values across all scanners. Analysis of the coefficients of variation CV revealed greater stability of measurements at the 0.50 mm gap, particularly with the Primescan. In contrast, the 0.25 mm gap showed greater dispersion of results, with high coefficients of variation at several locations, suggesting lower repeatability of measurements under this condition.

Table 5 presents the results of the factor analysis of the linear measurements of the canine tooth, considering the effects of the scanner, the gap, and the scanner-versus-gap interaction at the six measurement points and on the overall mean.

Table 6 - Results of the factorial rank analysis: scanner and gap effects on canine measurements

Analysis	Canine – measurements						
	Disto - buccal	Buccal	Mesio - buccal	Disto – palatal	Palatal	Mesio-palatal	Global
Scanner Factor - TS (p)	3,698 (0,031)	10,332 (<0,001)	20,280 (<0,001)	2,627 (0,082)	1,089 (0,344)	21,674 (<0,001)	37,567 (<0,001)
Scanner - Effect - η^2	0,120	0,277	0,429	----	----	0,445	0,582
GAP Factor - TS (p)	34,074 (<0,001)	76,384 (<0,001)	122,551 (<0,001)	153,365 (<0,001)	107,767 (<0,001)	60,280 (<0,001)	382,911 (<0,001)
GAP - Effect - η^2	0,387	0,586	0,694	0,740	0,666	0,527	0,876
Scanner*GAP - TS (p)	16,982 (<0,001)	1,158 (0,322)	1,189 (0,312)	2,226 (0,118)	1,145 (0,326)	1,561 (0,219)	1,435 (0,247)
Scanner*GAP - Effect - η^2	0,386	----	----	-----	-----	-----	----
Bonferroni Post Hoc	Trios 4/ Primescan	Trios 4 from others	Trios 4/ Primescan	------	------	Primescan from others	Differences among all

TS (p) - Test Statistic (p-value).

The factor analysis presented in Table 5 regarding the positions revealed that, in the linear measurements of the canine, the scanner factor had a statistically significant effect in the disto-vestibular, vestibular, mesio-vestibular, and mesio-palatal regions, as well as in the overall mean. No significant differences were observed between scanners in the disto-palatal and palatal regions. The gap factor had a statistically significant effect on all measurements analyzed, with a particularly high magnitude in the overall mean, highlighting the influence of gap depth on linear measurements of the canine. The scanner versus gap interaction was significant only in the disto-vestibular region, indicating that, at this specific location, the effect of the gap varied depending on the scanner used. Post hoc tests indicated significant differences between Trios 4 and Primescan in the disto-vestibular and mesio-vestibular regions, significant differences between Trios 4 and the other scanners in the vestibular region, significant differences for Primescan in the mesio-palatal region, and differences among all scanners in the overall mean.

4.1.3 Spatial and Tooth Type Comparisons

Table 6 presents the results of the Friedman test, which was used to compare the six linear measurements for each tooth, by scanner and gap level.

Table 7 - Friedman test results for the comparison of linear measurements within each tooth type

Scanner	GAP	Molar TS (p)	Canine TS (p)
Primescan	0.50 mm	46,98 (<0,001)	43,51 (<0,001)
	0.25 mm	34,30 (<0,001)	20,90 (<0,001)
Trios 4	0.50 mm	35,14 (<0,001)	27,60 (<0,001)
	0.25 mm	6,10 (0,297)	3,82 (0,576)
Trios 6	0.50 mm	44,61 (<0,001)	26,46 (<0,001)
	0.25 mm	18,01 (<0,001)	25,51 (<0,001)

ET (p) –Friedman Test Statistics

The Friedman test (**Table 6**) proved that the six linear measurement locations did not behave homogeneously, showing significant differences ($p < 0.001$) under almost all experimental environments. The sole exception occurred with the Trios 4 scanner at a 0.25 mm gap, where no significant spatial variations were found in either the molar ($p = 0.297$) or canine ($p = 0.576$).

Table 7 presents the results of the Wilcoxon test, which was used to compare, within each scanner and for each gap level, the linear measurements of the molar with those of the canine.

Table 8 - Wilcoxon signed-rank test results for the comparison of each linear measurement between molar and canine teeth

Scanner	GAP	Test Statistics	Molar versus Canine						
			Disto - buccal	Buccal	Mesio - buccal	Disto – palatal	Palatal	Mesio- palatal	Global
Primescan	0.50 mm	TS	-1,887	-2,809	-2,805	-2,807	-2,805	-1,790	-2,803
		p	0,059	0,005	0,005	0,005	0,005	0,074	0,005
	0.25 mm	TS	-2,803	-2,090	-1,376	-1,988	-2,805	-2,652	-2,397
		p	0,005	0,037	0,169	0,047	0,005	0,008	0,017
Trios 4	0.50 mm	TS	-2,499	-2,805	-0,051	-1,788	-0,255	-2,191	-0,357
		p	0,012	0,005	0,959	0,074	0,799	0,028	0,721
	0.25 mm	TS	-0,767	-1,786	-2,497	-1,530	-0,671	-1,429	-1,988
		p	0,443	0,074	0,013	0,126	0,502	0,153	0,047
Trios 6	0.50 mm	TS	-1,682	-2,805	-2,703	-0,867	-0,255	-0,306	-0,866
		p	0,093	0,005	0,007	0,386	0,799	0,759	0,386
	0.25 mm	TS	-0,770	-1,886	-1,362	-2,075	-1,581	-2,553	-0,459
		p	0,441	0,059	0,173	0,038	0,114	0,011	0,646

ET (p) –Wilcoxon Test Statistics

In table 7 was concluded that, when comparing linear measurements between molars and canines using the Wilcoxon test, there are statistically significant differences at various locations, although with distinct patterns across scanners and gap levels. In Primescan, significant differences were observed in most measurements, including the overall mean for both gaps, suggesting that tooth type consistently influences the measurements obtained by this scanner. In Trios 4, the differences were more localized, with significance observed in some specific regions and in the overall mean only for the 0.25 mm gap ($p = 0.047$). In Trios 6, the differences between molars and canines were concentrated in specific locations, with no significant differences observed in the overall mean. Overall, the results indicate that the behavior of linear measurements differs between molars and canines, but this difference depends on the scanner, the gap, and the region considered.

4.2 RMS Analysis

The Root Mean Square (RMS) values were calculated to quantify digitized surface errors across the prepared tooth structure and the subgingival area (*infra gingival*). Descriptive statistics are presented below (**Table 8)**

Table 9 - Characterization of the obtained RMS values

Scanner	GAP	Descriptive Metrics	RMS Values			
			Molar abutment	Infra gingival molar	Canine abutment	Infra gingival canine
Primescan	0.50 mm	$\bar{X}$±s	0,061±0,013	0,079±0,019	0,052±0,019	0,048±0,016
		CV	20,86%	22,97%	36,58%	32,57%
		CI 95%	[0,052 – 0,070]	[0,066 – 0,092]	[0,039 – 0,066]	[0,037 – 0,060]
	0.25 mm	$\bar{X}$±s	0,131±0,009	0,060±0,010	0,054±0,008	0,081±0,018
		CV	7,12%	16,36%	14,00%	22,16%
		CI 95%	[0,124 – 0,137]	[0,053 – 0,067]	[0,048 – 0,059]	[0,068 – 0,094]
Trios 4	0.50 mm	$\bar{X}$±s	0,052±0,011	0,063±0,014	0,042±0,004	0,056±0,007
		CV	20,51%	22,57%	10,61%	12,86%
		CI 95%	[0,044 – 0,059]	[0,053 – 0,073]	[0,039 – 0,045]	[0,056 – 0,061]
	0.25 mm	$\bar{X}$±s	0,095±0,005	0,032±0,006	0,045±0,004	0,048±0,015
		CV	5,15%	17,62%	8,14%	31,93%
		CI 95%	[0,092 – 0,099]	[0,032 – 0,036]	[0,042 – 0,047]	[0,037 – 0,058]
Trios 6	0.50 mm	$\bar{X}$±s	0,044±0,008	0,061±0,014	0,044±0,013	0,055±0,014
		CV	19,34%	23,21%	30,72%	25,79%
		CI 95%	[0,038 – 0,050]	[0,051 – 0,071]	[0,044 – 0,0,53]	[0,045 – 0,066]
	0.25 mm	$\bar{X}$±s	0,080±0,005	0,044±0,011	0,046±0,006	0,062±0,020
		CV	6,52%	24,18%	13,73%	32,16%
		CI 95%	[0,077 – 0,084]	[0,044 – 0,052]	[0,041 -,0,050]	[0,048 – 0,076]

$\bar{X}$±s – mean ± standard deviation; CV – coefficient of variation; CI 95% - confidence interval for the mean 95%

At the molar preparation, a clear increase in RMS values was observed at the 0.25 mm gap for all scanners, with this increase being most pronounced in the

Primescan (0.061±0.013 to 0.131±0.009). Within this segment, the Bonferroni post hoc test revealed significant differences among all three scanners tested, Trios 6 maintained the lowest mean RMS values (0.044 at 0.5 mm and 0.080 at 0.25 mm), suggesting superior digitized precision.

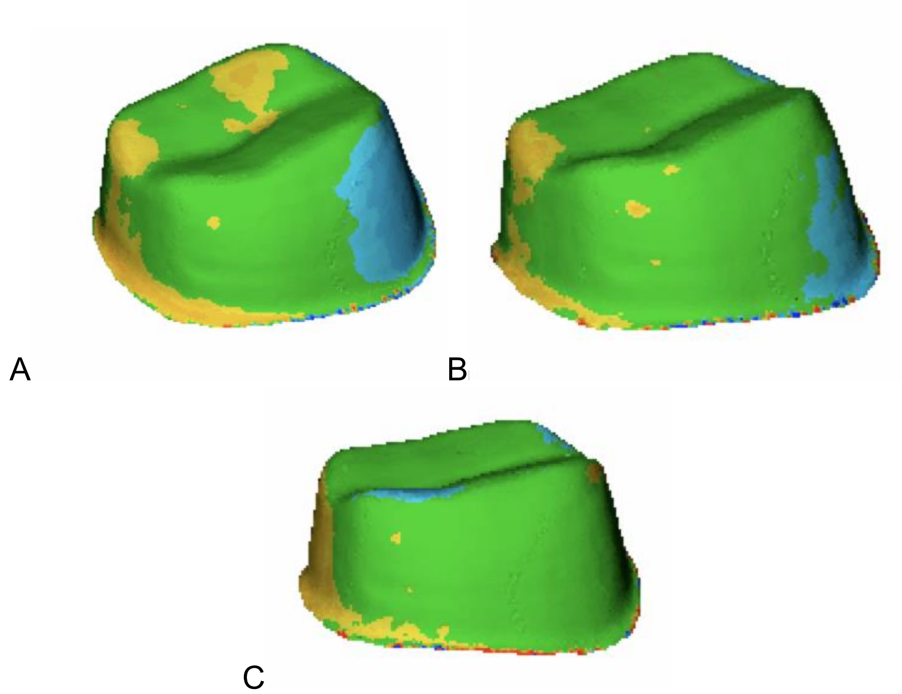
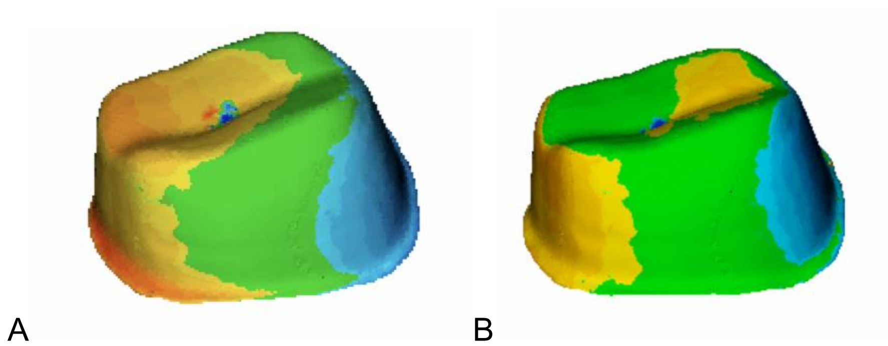
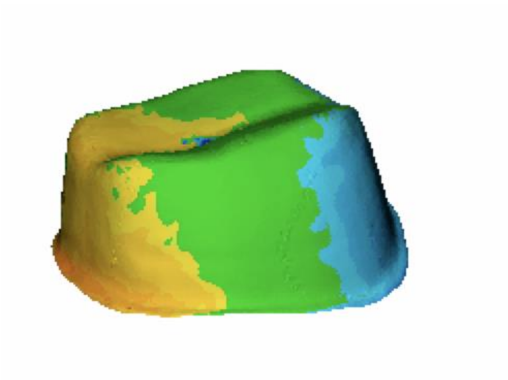


Figure 9 - RMS color coded map of molar abutment at a gap of 0.25 mm. A, Primescan; B, Trios 4; C, Trios 6

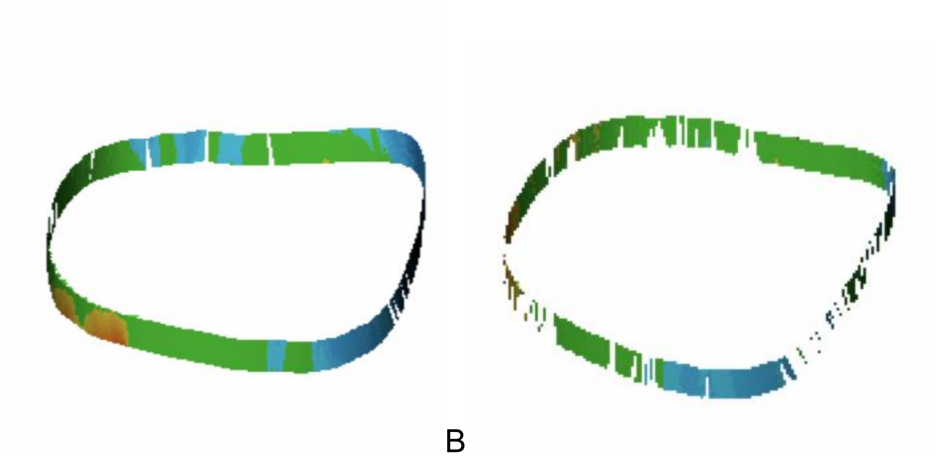




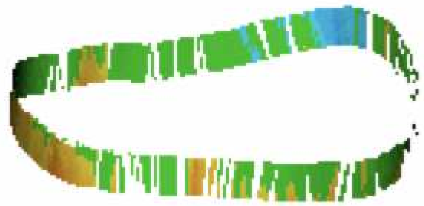
C

Figure 10 - RMS color coded map of molar abutment at a gap of 0.5 mm. A, Primescan; B, Trios 4; C, Trios 6

Conversely, in the subgingival molar region displayed an opposite pattern, where RMS values dropped at the 0.25 mm gap, a shift most pronounced in Trios 4 (0.032±0.006), therefore the gap factor remained a dominant predictor of distortion.



A B



C

Figure 11 - RMS color coded map of infragingival molar at a gap of 0.25 mm. A, Primescan; B, Trios 4; C, Trios 6.

On the canine preparation, RMS values were relatively similar across scanners and across gap levels, suggesting that this variable has less influence in this region. However, within the subgingival canine region, the behavior varied among scanners, with an increase in RMS on the Primescan and Trios 6 at a 0.25 mm gap, but a decrease on the Trios 4. These results suggest that scanning error depends not only on the scanner and the gap, but also on the region being evaluated.

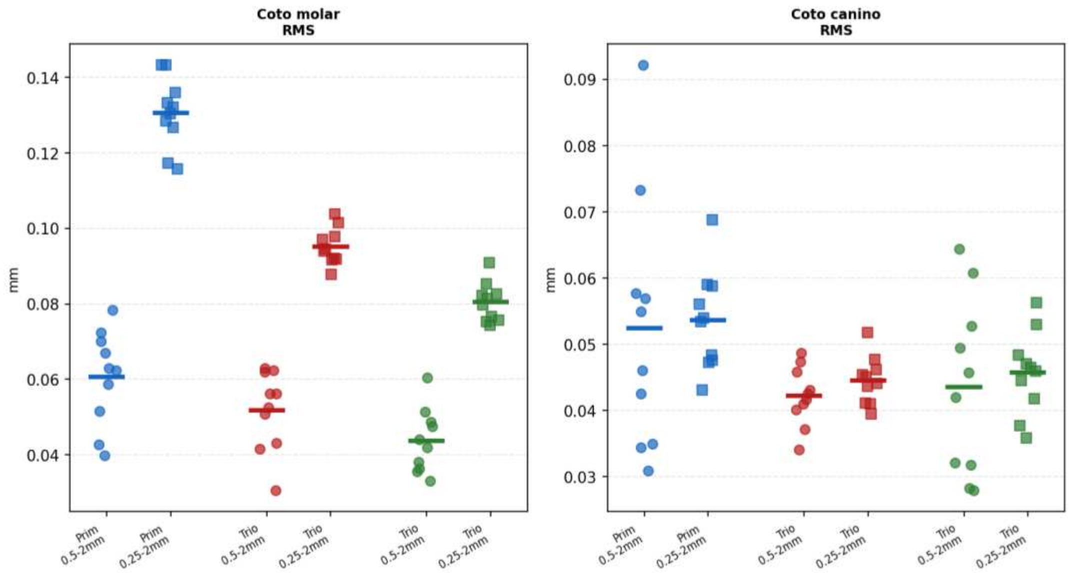
A B

C

Figure 12 - RMS color coded map of infragingival canine at a gap of 0.25 mm. A, Primescan; B, Trios 4; C, Trios 6.

Table 9 presents the results of the factor analysis of the positions for the RMS values, considering the effects of the scanner, the gap, and the interaction between the scanner and the gap, this analysis confirmed that the scanner factor was statistically significant for the molar preparation, subgingival molar, and canine preparation ($p < 0.05$).

To complement the descriptive RMS analysis, the distribution of all individual RMS measurements was evaluated. Figure 13 illustrates the variability of the scanners under both gap conditions and provides a visual representation of the consistency of the measurements obtained for each system.



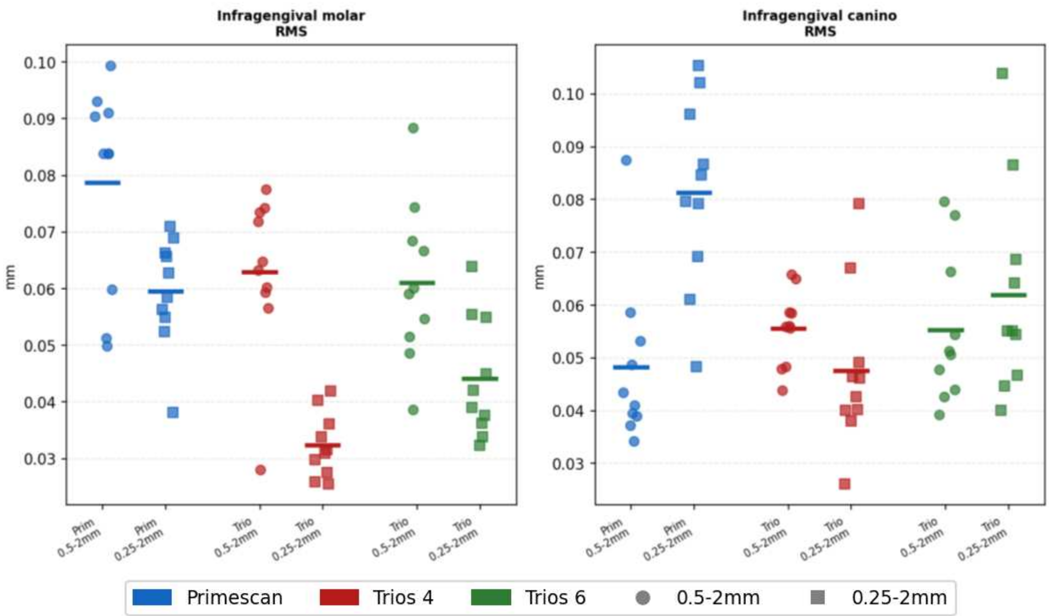


Figure 13 - Jitter plots of all individual scan RMS values. Circles represent the 0.5 mm depth, squares represent the 0.25 mm depth. Horizontal bars indicate group means.

The distribution of individual RMS values is shown in Figure 13. The jitter plots demonstrate the variability of each scanner under both gap conditions, with circles representing the 0.5 mm gap and squares representing the 0.25 mm gap. Primescan showed greater dispersion and higher RMS values in some conditions, particularly at the 0.25 mm gap, whereas the Trios scanners generally presented lower and more clustered RMS values. This visual distribution supports the numerical RMS findings and highlights the different behaviour of the scanners under restricted optical access.

Table 10 - Factorial analysis results on ranks: Scanner and Gap factor for RMS values

Analysis	RMS Values			
	Molar abutment	**Infra gingival molar**	**Canine abutment**	**Infra gingival canine**
Scanner Factor -TS (p)	37,927 (<0,001)	12,048 (<0,001)	4,994 (0,010)	1,653 (0,201)
Scanner – Effect - η^2	0,584	0,309	0,156	----

GAP Factor - TS (p)	376,280 (<0,001)	40,866 (<0,001)	2,378 (0,129)	4,064 (0,049)
GAP - Effect - η^2	0,875	0,431	-----	0,070
Scanner*GAP - TS (p)	2,214 (0,119)	3,038 (0,056)	0,229 (0,796)	11,143 (<0,001)
Scanner*GAP - Effect - η^2	-----	----	----	0,292
Bonferroni Post Hoc	Differences among all	Primescan from others	Trios 4/ Primescan	------

TS (p) - Test Statistic (p-value).

Based on the factor analysis of the positions applied to the RMS values, a statistically significant effect of the scanner was observed in the molar abutment, the subgingival molar region, and the canine abutment. The effect was particularly pronounced in the molar abutment, where significant differences were observed among all scanners. The gap factor had a significant effect on the molar abutment, the subgingival molar region, and the subgingival canine region, although the effect size was reduced in the latter. In the canine abutment, the effect of the gap was not statistically significant. The scanner versus gap interaction was significant only in the canine subgingival region, indicating that, at this location, the effect of gap depth varied depending on the scanner used. These results suggest that the scanning error, expressed by the RMS, depends on the region evaluated, with the molar abutment being the region most sensitive to differences between scanners and to variations in the gap.

To further investigate the influence of scanner type and gingival gap width on scanning accuracy, the distribution of RMS values obtained in the palatal region was analyzed. The objective of this analysis was to determine whether the differences observed in the descriptive statistics were maintained when the complete distribution of RMS values was considered. Figure 14 illustrates the RMS distributions for both gap conditions (0.25 mm and 0.5 mm), allowing a visual comparison of scanner behaviour under different levels of optical accessibility.

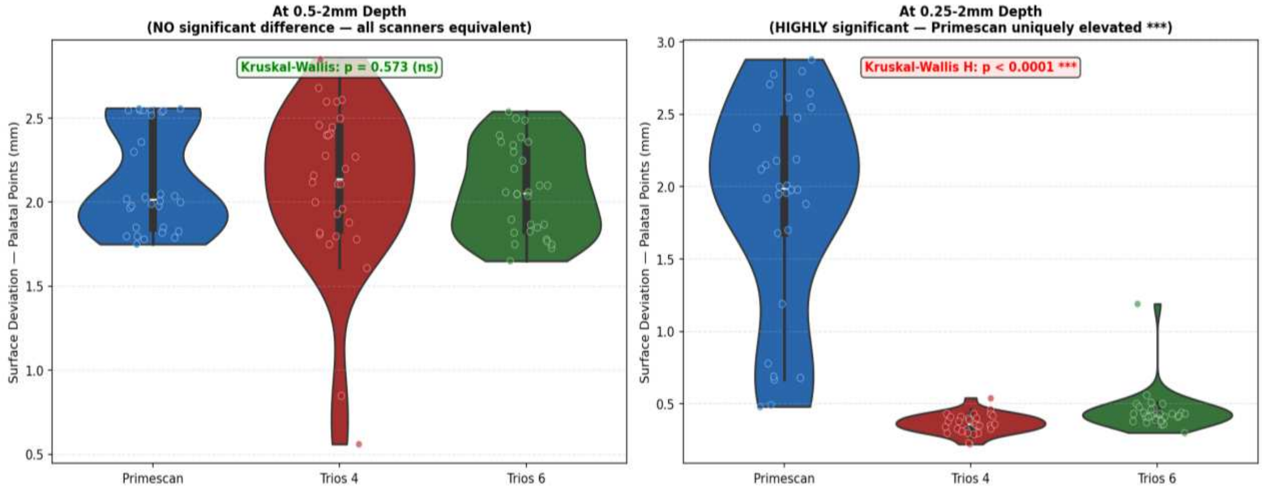


Figure 14 - Palatal surface deviation distributions at each depth condition. Left: 0.5 mm. Right: 0.25 mm.

For palatal deviation distributions, a depth dependent pattern was observed in figure 14. At the 0.5 mm gap, no statistically significant differences were found among scanners (KW p=0.573), suggesting similar behaviour under a better optical access. However, ate the 0.25 mm gap, a highly significant difference was observed (KW p<0.0001), with Primescan showing higher values compared to both Trios scanners. This indicates that scanner-relate differences became more evident when the gap was reduced.

4.3 Correlation Between RMS and Depth of Reading

Spearman's rank correlation coefficients (ρ) were calculated to explore potential associations between 3D digitized surface errors (RMS) and local linear depth measurements.

4.3.1 Molar correlations

As demonstrated in **Table 10** , the correlations between RMS and linear measurements on the molar were sporadic and strictly dependent on the specific experimental conditions.

Table 11 - Spearman's correlation between RMS measurements and linear measurements of the molar and overall molar means

Scanner	GAP	RMS	Molar – measurements						
			Disto - buccal	Buccal	Mesio - buccal	Disto – palatal	Palatal	Mesio-palatal	Global
Primescan	0.50 mm	Abutment	0,739*	-0,129	0,603	-0,442	0,341	-0,032	0,559
		Infra gingival	0,679*	-0,242	0,604	-0,399	0,235	0,112	0,523
	0.25 mm	Abutment	-0,226	-0,742*	-0,558	-0,288	-,091	-0,030	-0,697*
		Infra gingival	-0,396	-0,754*	-0,479	-0,322	-0,467	-0,515	- 0,806**
Trios 4	0.50 mm	Abutment	0,064	0,482	0,771**	-0,404	0,255	0,286	0,043
		Infra gingival	0,316	0,538	0,468	-0,085	0,794**	0,758*	0,515
	0.25 mm	Abutment	-0,061	-0,622	-0,049	0,322	-0,274	0,345	-0,103
		Infra gingival	0,213	-,439	-0,304	0,529	-0,067	0,127	-0,224
Trios 6	0.50 mm	Abutment	0,590	0,419	0,345	-0,280	0,438	0,243	0,697*
		Infra gingival	0,365	0,334	0,200	-0,098	0,292	0,103	0,503
	0.25 mm	Abutment	-0,309	-0,353	0,036	-0,092	0,555	0,382	0,176
		Infra gingival	-0,552	-0,638*	0,036	-0,632*	0,116	0,244	-0,188

* - correlation is significant at 5%; ** - correlation is significant at 1%.

Table 9 shows that the correlations between RMS and linear measurements of the molar are sporadic and dependent on the experimental conditions. Positive correlations predominate at a 0.50 mm gap, such as the significant associations between Primescan disto-buccal site and both preparation RMS ($\rho = 0.739$, $p < 0.05$) and subgingival RMS ($\rho = 0.679$, $p < 0.05$), while negative correlations are more common at a 0.25 mm gap highlightable by Primescan buccal site vs.

subgingival RMS (ρ = -0.754, p < 0.05) and its global linear mean vs. subgingival RMS (ρ = -0.806, p < 0.01). There is, therefore, no consistent overall relationship between RMS and all linear measurements, the association depends on the scanner, the gap, and the analyzed area.

4.3.2 Canine Correlations

The canine correlation analysis (**Table 11**) confirmed that significant associations were primarily restricted to the Trios 4 system, manifesting as strong positive correlations, particularly at the global linear mean level under the 0.5 mm gap (p < 0.01).

Table 12 - Spearman's correlation between RMS measurements and linear measurements of the canine tooth and the overall mean for the canine tooth

Scanner	GAP	RMS	Canine – measurements						
			Disto - buccal	Buccal	Mesio - buccal	Disto – palatal	Palatal	Mesio-palatal	Global
Primescan	0.50 mm	Abutment	-0,152	-0,109	-0,134	-0,013	-0,458	0,195	-0,024
		Infra gingival	0,462	0,488	0,001	0,182	-0,207	-0,537	0,043
	0,25 mm	Abutment	-0,382	-0,455	-0,455	-0,061	-0,166	0,188	-0,491
		Infra gingival	-0,055	-0,321	-0,855**	-0,097	0,160	0,273	-0,661*
Trios 4	0.50 mm	Abutment	-0,018	0,103	0,523	0,456	0,354	0,614	0,806**
		Infra gingival	0,127	-0.024	0,146	0.201	0,590	0,766**	0,733*
	0.25 mm	Abutment	0,366	-0,412	-0,049	-0,373	0,085	-0,288	0,182
		Infra gingival	-0,012	0,228	0,146	-0,177	-0,085	0,828**	0,146
Trios 6	0.50 mm	Abutment	-0,442	0,212	0,255	0,024	-0,236	0,001	-0,224
		Infra gingival	-0,176	-0,309	0,061	-0,196	0,055	0,249	-0,248
		Abutment	-0,135	-0,127	-0,590	0,177	-0,396	0,202	-0,418

	0.25 mm	Infra gingival	-0,469	0,164	-0,296	0,080	-0,144	-0,092	-0,049

* - correlation is significant at 5%; ** - correlation is significant at 1%.

Table 10 suggests that, in the canine abutment, correlations between RMS and linear measurements are more evident in the Trios 4, particularly in a positive direction. In the Primescan, significant correlations appear only at the 0.25 mm gap and are negative. In Trios 6, there are no significant correlations. Thus, the association between RMS and linear measurements of the canine clearly depends on the scanner and the experimental conditions.

4.4 Summary of Main Findings

In summary, the results indicate that the accuracy and scanning error of intraoral scanners are influenced by multiple factors, depending on the type of scanner, the depth of the gap, the tooth being scanned, and the location of the measurement. Linear measurements generally showed higher values in the 0.50 mm gap compared to the 0.25 mm gap, with the latter associated with greater variability and lower repeatability under various conditions. The gap proved to be the most consistent factor in explaining the observed differences, showing significant effects on all linear measurements of the molar and canine. The scanner also had a significant influence in several regions, although to a greater extent depending on the region.

Analysis of the RMS values showed that scanning error varies depending on the region evaluated. The molar stump was the region most sensitive to differences between scanners and to variations in the gap, with the Trios 6 standing out for having the lowest RMS values in this region. On the other hand, in the canine subgingival region, a significant interaction between scanner and gap was observed, indicating that the effect of gap depth was not the same for all scanners. The correlations between RMS and linear measurements were sporadic and dependent on the experimental condition, making it impossible to identify a uniform overall association between error and linear measurements.

The results also demonstrated that the six measurement locations do not behave homogeneously, as the Friedman test revealed significant differences between regions in most of the analyzed conditions. The comparison between molars and canines also revealed significant differences in several regions, particularly on the Primescan, suggesting that tooth type should be considered when interpreting scanner accuracy. Overall, the data suggest that the assessment of intraoral scanner accuracy must simultaneously consider the equipment used, the gap depth, the tooth being evaluated, and the specific measurement region.

Table 13 - Summary findings of scanner performance

Scanner	Trueness/Precision	Subgingival data acquisition	Interpretation
Primescan	Least trueness and lower precision, although with the highest depth of reading in subgingival area and overall	Highest	Achieved the greatest depth of reading and most complete subgingival acquisition, although associated with a higher RMS value.
Trios 4	High trueness and precision, Lower RMS values in subgingival areas	Lowest	Demonstrated low RMS values with a limited depth of reading mostly ate the 0.25 mm gap.
Trios 6	Highest trueness, high precision Lower RMS values in subgingival areas	Low	Demonstrated low RMS with the highest measurements consistency, while a lower than Primescan depth of reading

Discussion

5. Discussion

5.1 Influence of Gap Size on Scanner Performance

The results of the present study clearly demonstrate that the width of the simulated gingival sulcus is one of the most critical factors affecting the IOSs performance. In a condition that is narrower (0.25 mm) we had significant differences and a lower reading in the gingival sulcus, representing the most challenging scenario. Similar findings were shown by Monaco et al. who explained that the depth of reading mostly decreases in a narrower and less accessible gingival sulcus. (8)

In the 0.25 mm gap, the Primescan showed a clear advantage in terms of depth reading when compared to Trios 4 and 6, this suggests that reduced space limits the optical access. The Primescan achieved a mean depth of reading of 1.23 mm in the 0.25 mm gap, whereas the Trios 6 and for reached mean values of 0.61 mm and 0.38 mm, respectively. This difference may be explained because of the IOSs technologies that each one use. The Primescan is based on high frequency structured light projection, allowing a better light penetration in the gingival sulcus even in areas with limited accessibility. In contrast, the Trios scanner use confocal technology, that only captures with focus and sufficient optical quality, which may limit the data acquisition in deeper or narrower areas. (1,3)

Nevertheless, when the gap is increased to 0.5 mm, all scanners showed an improvement in the depth reading with similar values reaching 2 mm. Increasing the available space for IOSs to read, allows a decrease in the limitations related to the IOSs technology. This result is also cited in Nishiyama et al. who demonstrated through 3D-printed models that increased gingival retraction improves optical capture in subgingival areas. Revilla-León et al. also emphasized the importance of adequate optical access and gingival retraction in order to improve the accuracy of scanners.(15,16) Therefore, the second null hypothesis (H_{02}), stating that gingival sulcus width does not significantly influence depth of reading, was rejected.

5.2 Relation Between Depth of Reading and RMS Values

One of the most paradoxical and scientifically important findings of this study was the relation between depth of reading and the RMS values obtained within the subgingival area. Primescan generally demonstrated a greater ability to penetrate within the gingival sulcus, it showed a higher RMS value, mostly in the subgingival area. Although the Trios scanners showed lower RMS values, these results do not necessarily correspond to a better clinical performance.

The RMS values from scanner do not actually represent superior clinical accuracy, but rather the deviation between the scanned surface and the reference model within the area that was effectively captured. When also analyzing with the linear measurements the Trios scanners reflected a selective data acquisition. Those results are from a lower depth of reading in the gingival sulcus than the Primescan particularly in the 0.25 mm gap. The superiority of the Primescan in depth of reading became important in the 0.25 mm gap, where it reached twice the depth than Trios 6 and triple the depth than Trios 4. Therefore, if the scanner captures a larger and more complex area of the tooth, the captured images may accumulate greater deviations, resulting in higher RMS values.

This finding may be explained by differences in the scanner algorithm and optical filtering strategies as mentioned, those differences are mostly from Trios and Primescan technology. The Trios scanner systems have a more conservative reading only where there is sufficient optical quality. Consequently, the RMS calculation is performed on a smaller reading with lower deviation values. In contrast, the Primescan appears to prioritize a more complete data acquisition even in areas where the light could be preventing a good reading quality, in this case the larger amount of capture data may also increase the probability of a higher deviation values. Róth et al. also discussed the acquisition algorithms and image processing. (20)

The present findings are in agreement with Monaco et al., who demonstrated a progressive reduction in scan quality as the depth of the gingival sulcus increased. Also, Zarone et al. showed a higher deviation when margins were positioned deeper in the sulcus. The current study expands these observations by demonstrating that deeper margins may be associated with higher RMS values mostly when IOSs are able of reading completely even in anatomically challenging areas. (7,8)Consequently, the fifth null hypothesis (H_{05}), which proposed the absence of a correlation between depth of reading and RMS values, was rejected.

Therefore, RMS values should not be analyzed independently from data completeness. A lower RMS value indicates a high precision in the captured images but at the same time masking incomplete reading of clinically relevant areas. This finding is clinically important for a successful prosthetic rehabilitation because a complete visualization of the preparation margin and accurate reproduction of the subgingival area is needed. Similar studies about the interpretation of trueness and precision in IOSs were shown and discussed by Sorrentino et al., Borbola et al. and Vag et al. (1,6,10) Future studies about this aspect, should also combine RMS with a quantitative surface coverage analysis also done in this study such as a linear measurement of the depth that scanners reached. Overall, the results indicate that the relationship between depth of reading and RMS is not linear. The ideal scanner is therefore not obviously the one with the lowest RMS but rather the one that achieves an optimal balance between the geometric trueness and subgingival access.

5.3 Influence of Geometry and Tooth Type

The statistical results revealed that the IOSs performance have different results across all tooth surfaces. The Friedman test (Table 9) confirmed that linear depth readings varied significantly in the six different ROIs. The palatal and disto-palatal regions always presented lower linear readings and higher variation with greater variability, which can be caused by the lower lighting in this area from the preparation walls preventing the light to reach deeply in the sulcus. (3,14)

Furthermore, the Wilcoxon test confirmed important differences between the molar and canine preparations. The molar was the most challenging condition for scanners with a horizontal shoulder margin, creates a flat floor that the increased gap such as 0.5 mm improves the light penetration and data acquisition within the sulcus. However, when the gap is narrower and goes to 0.25 mm this margin becomes darker from the adjacent gingiva.

In contrast, the canine's vertical preparation geometry alters how light interact with the tooth. As exposed by Sorrentino et al. and Zarone et al., vertical preparation allows the IOSs light to go completely parallel to the tooth, preventing shadows to appear in the gingival sulcus, so that the light can go through the gingival sulcus and reflect to the optical sensor of the scanner. This explains why the RMS values from the canine preparation were highly stable while the infra gingival area from the molar data kept being unstable. Finally, the unique anatomy of each tooth type directly influences the scanner´s optical path, meaning that horizontal and vertical margin should be treated from different approaches during digital clinical impressions. (5–7)

Differences observed indicate that scanner performance is affected by the geometric characteristics of the preparation. Therefore, the third null hypothesis (H_{03}) was rejected. Furthermore, significant differences were identified among the evaluated scanners regarding their depth of reading performance. As a result, the first null hypothesis (H_{01}), was also rejected. In addition, differences in RMS values were observed between scanners and experimental conditions, demonstrating that geometric accuracy was influenced by both the scanner used and the tested configurations. Therefore, the fourth null hypothesis (H_{04}) was also rejected.

5.4 Clinical Implications

From a clinical and practical side, these findings indicate that clinicians should not rely alone on the IOSs and captured data from them. If the scanner software does not automatically smooth out an unreadable subgingival margin to present at the end a clean 3D model the resulting definitive restorations will not be a good fit for the preparation.(12,22)

Results also demonstrated that insufficient gingival retraction compromises IOSs performance. In a narrower gap such as 0.25 mm, Primescan subgingival error reached a 0.131 mm, which exceeds the clinical limit. This indicates that even with a more advanced scanner, with superior depth reading, they rely on adequate retraction of the gingiva in order to not compromise the final restorations. Therefore, proper mechanical gingival retraction techniques, such as double cord retraction remain essential before any digital impression, and clinicians should not assume that scanner technology alone can compensate for inadequate gingival retraction. (15,16,18,19)

Overall, the results suggest that successful digital impressions depend on a combination of scanner performance, preparation design and adequate gingival management. Regardless of the scanner used, proper tissue displacement remains essential to obtain complete and clinically reliable digital impressions.

5.5 Study Limitations and Future Perspectives

Despite the relevant findings of this study some limitations should also be considered. First, this was an in vitro study under highly controlled conditions which do not fully reproduce the complexity of the intra oral conditions. Clinical factor such as saliva, blood, oral respiration, and patient movement during the scanning were absent in this case during the scanning and those factors may interfere with IOSs performance in a real clinical case. Furthermore, the gingival conditions were standardized, which may also differ from real soft tissues in a patient´s mouth. A real clinical case could be interesting to include in a future study.

Additionally, the models were printed with resin that allows a high standardization, but resin materials could not perfectly reproduce the optical aspect of a natural teeth and gingival tissue would, probably influencing light reflection and data acquisition. Finally, the sample size was sufficient for this experimental study, larger data would improve the robustness of the finding, and could be considered to future studies with additional repetitions and more complex experimental designs.(1,2,8,10)

Looking into future perspectives, the combined use of an AI within IOS software as already discussed by Róth et al. could be an immense improvement. Advanced AI algorithms could be trained to detect a better subgingival area and margin and alert the clinician if needed to do a localized rescan where required. However, because AI improvement relies mostly on data sharing networks, the ethical and privacy should not be put aside by dental practices. (20,21)

Conclusion

6. Conclusion

Within the limitations of this in vitro study, the findings showed that IOSs performance in subgingival areas is strongly influenced by the gap used in the sulcus, preparation geometry and scanner technology. Indeed, all scanners demonstrated a better performance with an increased gap from 0.25 mm to 0.5 mm, also proving the importance of optical access for reading accuracy.

The Primescan revealed the most reading depth under restricted conditions, mostly in the 0.25 mm gap, far exceeding the depth of Trios 4 and 6. However, this high reading depth also associates with a higher RMS value in some areas, especially in the horizontal molar preparation. This should be taken into consideration when choosing which IOSs is more clinically appropriate for different clinical cases.

In contrast, as one of the most relevant parts of this study the Trios scanner generally showed a lower RMS, nevertheless this should not be interpreted independently as superior clinical accuracy. The present study suggests that these lower RMS value may be from a more selective data acquisition from those scanners, where areas with less optical access and quality are not completely captured. This also shows the importance of analyzing all the information and results altogether.

Preparation geometry also had a major influence on IOSs performance. Horizontal molar preparation demonstrated a more difficult scanning ability, with increased RMS values and a lower depth reading, than the vertical canine preparation showed. When choosing a digital impression method, the preparation type should also be taken into consideration for a successful final restoration. For the best clinical results adequate soft tissue management and sufficient gingival retraction are also fundamental independently of scanner technology.
The null hypothesis was rejected, since significant differences were observed among scanners, gap widths and preparation geometries. Additionally, the

results suggested a relation between depth of reading and RMS values, showing that lower geometric deviations do not necessarily correspond to a more complete acquisition of subgingival anatomy.

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Annexes

8. Annexes

Annex 1 Safety Data Sheet – Phrozen Aqua Gray 8K Resin (Phrozen Tech Co., Ltd.) (23)

phrozen

SAFETY DATA SHEET

Phrozen Aqua Gray 8K Resin

Prepared according to US OSHA HCS 29 CFR 1910.1200.
Issued Date : 2021/11/19 *Page 1 of 12*

SECTION 1: IDENTIFICATION

Product identifier

Product name: Aqua Gray 8K Resin

Recommended use of the product and restriction on use

Relevant identified uses: For use in Phrozen 3D-printers
Uses advised against: Applications that generate aerosol, mist or vapor

Manufacturer or supplier details

Manufacturer: Phrozen Tech Co., Ltd.
287 Niupu Rd, Xiangshan Dist, Hsinchu City 30091, TAIWAN
Emergency telephone number: +886-3540-0076

SECTION 2: HAZARD IDENTIFICATION

Label elements:

Hazard pictograms:

Signal word: WARNING

Risk phrases:

R22 - May be harmful if swallowed
R36/37/38 - Irritation to eyes, respiratory system and skin
R43 - May cause sensitization by skin contact

Safety phrases:

S7 - Keep container tightly closed
S9 - Keep container in a well-ventilated place
S20 - When using do not eat or drink
S24/25 - Avoid contact with skin and eyes
S26 - In case of contact with eyes, rinse immediately with plenty of water and seek medical advice.
S28 - After contact with skin, wash immediately with plenty of water
S29 - Do not empty into drains
S37/39 - Wear suitable gloves and eye/face protection

Hazard statements:

H303 - May be harmful if swallowed
H315 - Cause skin irritation
H317 - May cause an allergic skin reaction
H318 - Cause serious eye damage

Precautionary statements:

P202 - Do not handle until safety precautions have been taken
P210 - Keep away from heat, hot surfaces, sparks, open flames and other ignition sources
P233 - Keep container tightly closed
P260 - Do not breathe dust/fume/gas/mist/vapors/spray
P261 - Avoid breathing dust, fume, gas, mist, vapors, spray
P262 - Do not get in eyes, on skin or on clothing
P264 - Wash thoroughly after handling
P271 - Use only outdoors or in a well-ventilated area. Hazardous polymerization may occur upon depletion of inhibitors.
P272 - Contaminated work clothing should not be allowed out of the workplace.
P273 - Avoid release to the environment.
P280 - Wear protective gloves/ eye protection/face protection.

Response:

P301+P317 - IF SWALLOWED: Get medical help.
P302+P352 - IF ON SKIN: Wash with plenty of water.
P305+P354+P338 - IF IN EYES: Immediately rinse with water for several minutes. Remove contact lenses, if present and easy to do. Continue rinsing.
P319 - Get medical help if you feel unwell.
P332+P317 - If skin irritation occurs: Get medical help.
P333+P317 - If skin irritation or rash occurs: Get medical help.
P362+P364 - Take off contaminated clothing and wash it before reuse.

Hazards not otherwise classified:

None

SECTION 3: COMPOSITION/INFORMATION ON INGREDIENTS

Components	CAS number	Weight %
Dipropylene Glycol Diacrylate	Proprietary	Proprietary
Epoxy acrylate	Proprietary	Proprietary
Acryloyl morpholine	Proprietary	Proprietary
Tris(2-Hydroxy Ethyl) Isocyanurate Triacrylate	Proprietary	Proprietary
Urethane acrylate	Proprietary	Proprietary
Silicon dioxide	Proprietary	Proprietary
Diphenyl(2,4,6-trimethyl benzoyl) phosphine oxide	75980-60-8	1-10%
Titanium dioxide	13463-67-7	<1%
Carbon black	1333-86-4	<1%

SECTION 4: FIRST AID MEASURES

Contact with skin:

Immediately take off all contaminated clothing. Wash skin immediately with mild soap/water for at least 15 minutes. If resin is not completely removed, use a waterless cleaner first. Seek medical advice if irritation persists.

Contact with eyes:

Wash eyes under the eyelid immediately with water for 20-40 minutes. See medical advice if irritation, pain, tears or redness persists.

Swallowing:

DO NOT INDUCE VOMITING. If vomiting occurs naturally, keep airways clear. Immediately obtain medical attention.

Inhalation:

If overcome by exposure, ventilate the premises. Remove victim from contaminated area to well ventilated areas or outdoors. If needed, provide oxygen or artificial respiration. Get immediate medical attention

SECTION 5: FIRE-FIGHTING MEASURES

Recommended extinguishers:

CO2, foam, chemical powders, sand or earth. Use water based extinguishing media with caution.

Extinguishers not to be used:

High volume water jet.

Risks arising from combustion:

Avoid inhaling the fumes. Incomplete combustion releases toxic gasses.

Advice for fire-fighters:

Wear self-contained breathing apparatus for firefighting if necessary.

SECTION 6: ACCIDENTAL RELEASE MEASURES

Measures for personal safety:

Use masks, gloves and protective clothing.

Environmental measures:

Limit leakages with earth or sand. If the product has flown off into a water course, into the drainage system, or has contaminated the ground vegetation, notify the responsible authorities.

Cleaning methods:

Rapidly collect the product. To do so, wear a mask and protective clothing. When the product is in a liquid form, stop it from entering the drainage system. Recover the product for re-use if possible, or for elimination in compliance with waste disposal regulations in force. The product might, when appropriate, be absorbed by inert material.

SECTION 7: HANDLING AND STORAGE

Handling precautions:

Avoid contact with and inhalation of vapors and/or dust. Do not eat or drink or smoke while working.

Incompatible materials:

Keep away from amines, strong bases, acids and strong oxidants.

Storage conditions:

Keep away from amines, strong bases, acids and strong oxidants. Storage temperature: between 15°C/59°C to 35°C/95°F Keep in a dry place, in t original containers tightly closed, avoid heat/ignition and light sources. Prevent contamination by foreign materials and water. For industrial use only, keep away from children.

SECTION 8: EXPOSURE CONTROLS/PERSONAL PROTECTION

Precautionary measures:

Provide adequate ventilation to the areas where the product is stored and/or handled.

Respiratory protection:

Required where ventilation/aspiration is insufficient or exposure is prolonged, or applications in which the product is sprayed or heated. Required in case of machini or applications that release dust.

Protection for hands:

Use protective gloves. For an extended exposure of the product, wear nitrile/neoprene gloves. Take note of the information given by the producer concerning permeability and break through times, and of special workplace conditions (mechanical strain, duration of contact). The exact break through time can be obtained from the protective glove producer and this has to be observed. Please observe the instructions regarding permeability and breakthrough time which are provided by the supplier of the gloves. Also take into consideration the specific local conditions under which the product is used, such as the danger of cuts, abrasion, and the contact time.

Eye protection:

Use safety goggles.

Protection for skin:

Use clothing that provides complete protection to the skin.

SECTION 9: PHYSICAL AND CHEMICAL PROPERTIES

Apperance and color	Gray viscous liquid
Odor	Typical acrylate
pH	N/A
Melting point	N/A
Boiling point	N/A
Flash point	> 110C/230F
Explosive properties	N/A
Combustion related properties	N/A
Specific gravity	1.18 g/cm^3 at 25C/77F
Viscosity	320-350 cps
Solubility in water	Insoluble
Solubility in organic solvents	Soluble in organic solvents
Vapor pressure	N/A
Volatile Characteristics	Negligible
Electrostatic Discharge	Safe
Electric Conductivity	Dielectric

SECTION 10: STABILITY AND REACTIVITY

Stability:

Stable when stored in original containers designed for use with light sensitive materials under 35C/95F in dark, cool places.

Conditions to avoid:

Storage > 38C/100F, exposure to light, loss of dissolved air, and contamination with incompatible materials.

Incompatible materials to avoid:

Polymerization initiators, including peroxides, strong oxidizing agents, alcohols, copper, copper alloys, carbon steel, iron, rust, and strong bases.

Hazardous decomposition product:

Hazardous decomposition products may include oxides of carbon, nitrogen and various hydrocarbon fragments.

Hazardous polymerization:

Hazardous polymerization may occur. Uncontrolled polymerization may cause rapid evolution of heat and increase in pressure that could result in violent rupture of sealed storage vessels or containers.

SECTION 11: TOXICOLOGICAL INFORMATION

Individual components of this product are not reported to produce mutagenic effects in humans. None of the components of this material are listed by IARC, NTP, OSHA or ACGIH as carcinogens.

Acute toxicity:

Product: May be harmful if swallowed.

Components:

Acryloyl morpholine: (Oral) Harmful. (Inhalation) LC50 (4 h) 1 mg/L air (rat)*. (Dermal) Not classified.

Photoinitiator:(Oral) LD50 > 2500 mg/kg body weight (rat)*. (Inhalation) Not available. (Dermal) LD50 > 5000 mg/kg body weight

(*data from ECHA REACH-dossier information)

Skin corrosion/irritation:
Product: Cause skin irritation
Component: No data available.

Eye damage/irritation:
Product: Cause eye damage
Component: No data available.

Skin/Respiratory sensitization:
Product: May cause an allergic skin reaction
Component: No data available.

Germ cell mutagenicity:
Product: Not classified based on available information
Component: No data available.

Carcinogenicity:
Product: Not classified based on available information
Component: No data available.

Reproductive toxicity:
Product: Not classified based on available information
Component: No data available.

STOT - Single exposure:
Product: Not classified based on available information
Component: No data available.

STOT - Repeated exposure:
Product: Not classified based on available information
Component: No data available.

Aspiration toxicity:
Product: Not classified based on available information
Component: No data available.

SECTION 12: ECOLOGICAL INFORMATION

Keep product from waterways and watersheds. This substance is not readily biodegradable. Dispose of in accordance with all applicable regulations.

Ecotoxicity:

Product: No data available
Component: No data available.

Persistence and degradability:

Product: No data available
Component: All main components are biodegradable in water (100%). Not readily biodegradable

Bioacumulative potential:

Product: No data available
Component: No data available.

Mobility in soil:

Product: No data available
Component:

Epoxy acrylate: Adsorption/desorption: log Koc-0.49 - 5.66 dimensionless @35C.*
(*data from ECHA REACH-dossier information)

Results of PBT and vPvB assessment:

The substances are not considered to be persistent, accumulative, and toxic (PBT). The substances are not considered to be very persistent and very bioaccumulating (vPvB).

SECTION 13: DISPOSAL CONSIDERATIONS

Waste treatment methods:

Dispose of in accordance with governmental regulations (community, national or regional). Contact a licensed professional waste disposal service to dispose of this mixture. As with all foreign substances, do not allow the substances to enter storm or sewer drainage systems. Avoid release into the environment.

Sewage disposal relevant information:

Do not empty into drains. Avoid release to the environment. Refer to special relevant and safety data sheets.

Contaminated Packaging:

Dispose of as unused product. Expose the open emptied container to light, then dispose.

SECTION 14: TRANSPORT INFORMATION

Land transport USDOT	Not classified as dangerous goods under transport regulations.
Sea transport IMDG	Not classified as dangerous goods under transport regulations.
Air transport IATA/ICAO	Not classified as dangerous goods under transport regulations.
Further information	N/A
Other requirements	N/A

SECTION 15: REGULATORY INFORMATION

United States regulations:

TSCA inventory listing*:

Components	CAS number	Weight %	Status
Dipropylene Glycol Diacrylate	Proprietary	Proprietary	Listed
Epoxy acrylate	Proprietary	Proprietary	Listed
Acryloyl morpholine	Proprietary	Proprietary	Listed
Tris(2-Hydroxy Ethyl) Isocyanurate Triacrylate	Proprietary	Proprietary	Listed

Urethane acrylate	Proprietary	Proprietary	Listed
Silicon dioxide	Proprietary	Proprietary	Listed
Diphenyl(2,4,6-trimethyl benzoyl) phosphine oxide	75980-60-8	1-10%	Listed
Titanium dioxide	13463-67-7	<1%	Listed
Carbon black	1333-86-4	<1%	Listed

** All the components present in this product at concentrations equal to or greater than 0.1% are listed, or excluded from listing, on the United States Environmental Protection Agency Toxic Substances Control Act (TSCA) inventory.*

Significant New Use Rule (TSCA Sec.5):

Not listed.

Export notification under TSCA Sec.12(b):

Not listed.

SARA Sec.302 extremely hazardous substances:

No chemicals in this material are subject to the reporting requirements of SARA Title III, Sec 302.

SARA Sec.313 toxic chemicals:

Pursuant to Title III of the Superfund Amendments and Reauthorization Act of 1986, (SARA) and 40 CFR 372 Part 372, this product does not contain chemicals at levels greater or equal to 0.1wt% subject to the reporting requirements under Section 313.

CERCLA:

Not listed.

California Prop.65, Safe Drinking Water & Toxic Enforcement Act:

This product does not contain chemicals at levels greater or equal to 0.1wt% which are known to the state of California to cause birth defects or other reproductive harm.

European Union regulations:

EINECS listing:

Components	CAS number	Weight %	Status
Dipropylene Glycol Diacrylate	Proprietary	Proprietary	Listed
Epoxy acrylate	Proprietary	Proprietary	Listed
Acryloyl morpholine	Proprietary	Proprietary	Listed
Tris(2-Hydroxy Ethyl) Isocyanurate Triacrylate	Proprietary	Proprietary	Listed
Urethane acrylate	Proprietary	Proprietary	Listed
Silicon dioxide	Proprietary	Proprietary	Listed
Diphenyl(2,4,6-trimethyl benzoyl) phosphine oxide	75980-60-8	1-10%	Listed
Titanium dioxide	13463-67-7	<1%	Listed
Carbon black	1333-86-4	<1%	Listed

REACH No.:

A registration number is not available for this substance as the annual tonnage does not require a registration or the registration is envisaged for a later registration deadline.

ESIS dangerous chemicals:

Not listed.

SECTION 16: OTHER INFORMATION

To the best of our knowledge the information contained herein is accurate. However, Phrozen Tech. Co. Ltd. makes no warranty, expressed or implied, regarding the accuracy of these results to be obtained from the use thereof. Although certain hazards are described herein, we cannot guarantee that these are the only hazards that exist. Phrozen Tech. Co. Ltd. assumes no responsibility for injury from the use of the product described herein.

END OF SAFETY DATASHEET