

T.C.
YEDİTEPE UNIVERSITY
INSTITUTE OF HEALTH SCIENCES
DEPARTMENT OF ORTHODONTICS

**EVALUATION OF THE EFFECTS OF THE
DIFFERENT DEBONDING TECHNIQUES ON
ENAMEL CRACKING IN CERAMIC BRACKETS
BY USING SCANNING ELECTRON MICROSCOPE**

DOCTOR OF PHILOSOPHY THESIS

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Istanbul - 2025

THESIS APPROVAL FORM

Institute : Yeditepe University Institute of Health Sciences
Program : Orthodontics PhD
Title of the Thesis : Evaluation of the Effects of the Different Debonding
Techniques on Enamel Crack in Ceramic Brackets by Using Scanning Electron
Microscope

Owner of the Thesis : Dt. Halil İbrahim Taşkın

Examination Date : 26.05.2025

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DECLARATION

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which has been accepted for the award of any other degree except where due acknowledgment has been made in the text.

Halil İbrahim Taşkın

ACKNOWLEDGEMENTS

I am profoundly appreciative to my advisor, Assistant Professor Can Arslan. He has been genuinely generous, facilitating the process significantly and consistently available whenever I required assistance. It is a profound privilege to be his doctoral student.

I am thankful for all my professors, specifically our Head of the Orthodontics Department, Prof. Dr. Derya ÇAKAN, for consistently instilling pride in her students and imparting her extensive knowledge. She has significantly influenced my PhD career and will remain a lasting presence in my profession.

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LIST OF ABBREVIATIONS

SEM	Scanning Electron Microscope
EMC / EMCs	Enamel Microcrack / Enamel Microcracks
ARI	Adhesive Remnant Index
SBS	Shear Bond Strength
OCT	Optical Coherence Tomography
COP	Confocal Optical Profilometry
3D	Three-dimensional
EBA	Enamel Bonding Agent
LODI	Lift Off Debonding Instrument
MD Wing	Mesio Distally Wing
MD Base	Mesio Distally Base
I-Base	Base Bracket base and occlusal tip debonding technique
DSP	Digital Signal Processing
ANOVA	Analysis of Variance
HSD	Honestly Significant Difference
HAP	Hydroxyapatite
ICC	Intraclass Correlation Coefficient
µm	Micro Meter
NCSS	Number Cruncher Statistical System
V-Dif	Vertical Difference
H-Dif	Horizontal Difference
O-Dif	Oblique Difference
IQR	Inter Quartile Range

ABSTRACT

Taşkin H İ.(2025) Evaluation of The Effects of the Different Debonding Techniques on Enamel Cracking in Ceramic Brackets by Using Scanning Electron Microscopy. Yeditepe University Institute of Health Sciences, Department of Orthodontics, PhD Thesis, İstanbul.

This study sought to assess the impact of five distinct debonding strategies on the creation and propagation of enamel microcracks during the removal of ceramic brackets adhered to bovine incisors, employing scanning electron microscopy (SEM) analysis. Sixty bovine incisors with unblemished labial surfaces were randomly allocated into five equal groups (n=12). Brackets were debonded utilising five distinct techniques: vertical plier installation (Group 1), mesio-distal wing compression (Group 2), mesio-distal base peeling (Group 3), incisal-cervical peeling (Group 4), and oblique base compression (Group 5). Data were examined via ANOVA, Kruskal-Wallis, and post-hoc analyses. All debonding procedures produced substantial increases in microcrack diameters relative to baseline values ($p<0.05$). The oblique base compression technique (Group 5) exhibited the most significant enhancement in vertical crack propagation (mean difference: $11.25\pm3.42\text{ }\mu\text{m}$), whereas the incisal-cervical peeling technique (Group 4) revealed the minimal microcrack propagation overall (mean differences: vertical $5.33\pm2.14\text{ }\mu\text{m}$, horizontal $2.58\pm1.17\text{ }\mu\text{m}$). The orientation of force applied during the debonding of ceramic brackets markedly affects the patterns of enamel microcrack propagation. The incisal-cervical peeling technique seems to inflict less harm on enamel integrity, whereas oblique force application leads to greater microcrack formation. These findings indicate that practitioners ought to utilise incisal-cervical directed forces during the removal of ceramic brackets to reduce the risk of enamel damage.

Keywords: Ceramic brackets, debonding techniques, enamel microcracks, scanning electron microscopy, bovine incisors

TÜRKÇE ÖZET

Taşkın H İ. (2025). Seramik Braketlerde Farklı Debonding Tekniklerinin Mine Çatlakları Üzerindeki Etkilerinin Elektron Mikroskobu ile Değerlendirilmesi Yeditepe Üniversitesi Sağlık Bilimleri Enstitüsü, Ortodonti Anabilim Dalı, Doktora Tezi, İstanbul.

Bu çalışma, seramik braketlerin sıgır kesici dişlerine yapıştırıldıktan sonra çıkarılması sırasında mine mikroçatlaklarının oluşumu ve yayılımı üzerindeki beş farklı debonding stratejisinin etkisini, taramalı elektron mikroskobu (SEM) analizi kullanarak değerlendirmeyi amaçlamıştır. Sağlam labial yüzeylere sahip altmış sıgır kesici diş rastgele beş eşit gruba (n=12) ayrılmıştır. Braketler beş farklı teknik kullanılarak çıkarılmıştır: dikey pens yerleştirme (Grup 1), mezio-distal kanat sökümü (Grup 2), mezio-distal taban sökümü (Grup 3), insizal-servikal sökümü (Grup 4) ve oblik taban sökümü (Grup 5). Veriler ANOVA, Kruskal-Wallis ve post-hoc analizleri ile incelenmiştir. Tüm debonding işlemleri, başlangıç değerlerine kıyasla mikroçatlak uzunluklarında önemli artışlar meydana getirmiştir ($p<0.05$). Oblik taban sıkıştırma tekniği (Grup 5), dikey çatlak yayılımında en belirgin artışı göstermiştir (ortalama fark: $11.25\pm3.42\ \mu\text{m}$), fakat insizal-servikal soyma tekniği (Grup 4) genel olarak en az mikroçatlak yayılımını ortaya koymuştur. (ortalama farklar: dikey $5.33\pm2.14\ \mu\text{m}$, yatay $2.58\pm1.17\ \mu\text{m}$). Seramik braketlerin çıkarılması sırasında uygulanan kuvvetin yönü, mine mikroçatlak yayılım yönlerini önemli ölçüde etkilemektedir. İnsizal-servikal söküm tekniği, mine bütünlüğüne daha az zarar verirken, oblik kuvvet uygulaması daha fazla mikroçatlak oluşumuna yol açmaktadır. Bu bulgular, uygulayıcıların mine hasarı riskini azaltmak için seramik braketlerin çıkarılması sırasında insizal-servikal yönlendirilmiş kuvvetler kullanmaları gerektiğini göstermektedir.

Anahtar Kelimeler: Seramik braketler, debonding teknikleri mine mikroçatlakları, elektron mikroskobu, sıgır kesici dişleri

1.INTRODUCTION

Striving to meet patients' needs, the orthodontic community has developed various types of appliances that are more aesthetically pleasing. From metal brackets to plastic and ceramic brackets, patients now have options that provide both functional and aesthetic advantages. Consequently, orthodontic treatment has become more accessible and appealing to a larger number of patients.

With patients showing greater interest in aesthetics, ceramic brackets are gaining popularity. The fundamental concern associated with these orthodontic attachments pertains to their elevated adhesive resistance to shearing forces during removal procedures, potentially resulting in irreversible structural damage to the dental enamel surface, manifested as fractures and lacerations.(1)(2) The magnitude of adhesive resistance to shearing forces is predominantly determined by multiple variables, including the selected etching methodology, the cohesive properties of the composite bonding agent, the structural integrity of the mineralized enamel substrate, and the procedural approaches employed during attachment removal.(1)

For expert orthodontists and fast-advancing technologies, nearly every patient can achieve a smile they will cherish for a lifetime. However, numerous questions arise regarding potential adverse alterations in the enamel structure during orthodontic treatment, particularly after the debonding process. Different techniques for removing brackets and cleaning up the enamel have been assessed and compared to find the most suitable and minimally damaging method. (3)

Numerous studies have shown that removing brackets results in permanent changes to the enamel, regardless of the debonding techniques and adhesive removal methods employed.(3–5) The stresses produced during debonding may lead to the formation of enamel microcracks (EMCs), a type of dental injury, along with alterations in their morphological features.(5–9) EMCs, frequently detectable by both patients and dentists, can undermine enamel integrity, lead to staining, and promote plaque deposition on the rough cracked surface, hence heightening vulnerability to carious lesions and adversely affecting the aesthetic aspect of the teeth.(5,10,11)

Several methods have been proposed for the removal of brackets to minimize enamel damage, including mechanical, ultrasonic, and electrothermal techniques. Although each method has demonstrated effectiveness in removing brackets, pliers are preferred due to their cost efficiency, ease of use, and ability to apply shear and tensile stresses effectively.(12,13)

A supplementary critical parameter involves the mechanical stress vectors applied via orthodontic instruments throughout the debonding protocol.(14) The implementation of such specialized appliances may precipitate structural alterations in the attachment apparatus, compromise the adhesive junction at either the appliance-resin boundary or the mineralized tissue-bonding agent interface, or alternatively, generate internal fractures within the adhesive matrix itself.(15)

The debonding process also involves the removal of residual adhesive from the tooth surface. This can be achieved through two techniques: 1) Using a band-removing plier or scaler to rub off the adhesive, or 2) Employing a carbide bur and angled handpiece for grinding. The preferred standard technique involves the use of a tungsten carbide bur with a handpiece. In the final stage, the dental surface should be polished with pumice to achieve a smooth enamel finish.(16) All methods for debonding, which utilize orthodontic cutters and debonding pliers, tend to leave a substantial amount of adhesive on the enamel surface.(17) When a strong bond with the enamel is formed, failure at the enamel-adhesive interface can cause tearing of the enamel surface. Therefore, it is preferable for the adhesive to remain on the enamel after debonding.(18,19)

Given that orthodontic treatment straddles the categories of pathological relief and cosmetic enhancement, it is imperative, in accordance with the principles of ethical medical care, to establish a definitive benefit-to-harm ratio.(5) Comprehending this fundamental principle has necessitated the publication of scientific publications addressing the impact of the brackets' removal technique on EMCs.(5) In the last twenty years, an increasing volume of research has concentrated on diverse subjects(6,20,21), including the distribution and frequency of cracks(22), their rising quantities and lengths, variations in the prevalence and severity of EMCs(12), and the assessment of particular attributes of EMCs, such as their quantity, orientation, and length.(5,7–9,23,24)

Progress in laboratory methodologies has led to the development of techniques for detecting EMC, including staining, transillumination, ultrasonography, and optical coherence tomography (OCT).(5,12,20,25–28) Various techniques, including scanning electron microscopy (SEM), stereomicroscopy, confocal optical profilometry (COP), and three-dimensional (3D) scanning methods, have demonstrated their suitability for both visualizing enamel microcracks (EMCs) and quantifying enamel substance loss, the precise depth of removed enamel, as well as conducting point or linear measurements of EMC parameters.(3,5,7–9,22,25–27,29,30)

This study aimed to examine the cracks and their orientations on the enamel surface following the removal of ceramic brackets in various directions. The alterations in the cracks resulting from the removal directions were also assessed. The investigations utilised Scanning Electron Microscopy (SEM) for a comprehensive study.

2.GENERAL INFORMATION

2.1. Enamel Microstructure and Its Mechanical Properties

Enamel, characterized by its complex microstructure that changes depending on its distance from the tooth's outer surface, plays a vital role in safeguarding the dentin and pulp. It is the most mineralized tissue in the human body, consisting of 96% mineral content, 1% protein, and 3% water by weight.(31) The mineral component consists of carbonated hydroxyapatite crystals, which are densely arranged into prisms with an approximate effective diameter of 5 μm . Each prism is separated by a thin layer, less than 1 μm thick, of protein-based organic matrix. These prisms primarily extend perpendicularly from the dentin-enamel junction (DEJ) outward towards the tooth's surface(32). The rods extend roughly perpendicularly from the dentin-enamel junction (DEJ) to the tooth's surface. However, upon detailed examination, their arrangement differs depending on their location: in the enamel closest to the tooth's surface, the rods are nearly parallel, whereas in enamel near the DEJ, they are organized into groups that are oriented obliquely to each other. (33) The enamel's microstructure, defined by the organization of its mineral and organic elements, contributes to its unique mechanical attributes, including elevated fracture toughness and mechanisms that resist crack propagation.(33)

Enamel exhibits three main mechanical properties: hardness, elasticity, and fracture behavior. It has been determined that enamel is an anisotropic material, indicating that its mechanical properties differ depending on its location, chemical composition, and the arrangement of the enamel rods.(32) (34,35) Studies have found that the hardness and elastic modulus of enamel, which are some of the elastic property indices, increase with distance from the DEJ. The enamel located near the tooth surface demonstrates the greatest hardness and elastic modulus. Upon assessing these characteristics based on absolute distance from the DEJ, the most pronounced gradient in these mechanical properties was observed within the cervical area.(32) The literature does not provide a consensus on the precise values of enamel's mechanical properties. Hardness is estimated to range from about 3 to 6 GPa, while the elastic modulus varies between 70 and 120 GPa. Some studies have identified a maximum hardness of 3.5 GPa at the tooth's surface, noting a gradual decrease from the enamel surface to the DEJ.(32,34) Additionally, the chemical components and degree of mineralization play a crucial role in determining the

mechanical properties of enamel. (32,34) Researches have shown that both hardness and elastic modulus are assertive correlated with calcium content.(34,36) In instances of hypomineralized enamel, there were statistically significant decreases in hardness and elastic modulus, even with relatively small reductions in mineral content.(37) It has been estimated that a decrease of approximately 3 GPa in elastic modulus might occur with a 1.0% reduction in the volume concentration of HAP.(38) Eventually, the mechanical properties of enamel vary depending on rod orientation, the arrangement of HAP crystals within each rod, and the specific position along the same rod.(34,37) Significant statistical variations in enamel's mechanical properties were detected both along and across the rod axis, with the lowest values for hardness and elastic modulus observed when measured perpendicular to the rod axis.(37,39) Therefore, for cracks parallel to the rods, less energy was required to induce fracture compared to those oriented perpendicularly to the rods. (40,41)

Regarding the fracture properties of enamel, it has been found that the internal enamel exhibits strong resistance to fracture, with crack growth resistance increasing from the outer surface towards the interior.(36,40,42) The enhancement in crack growth resistance within the inner enamel is due to various toughening mechanisms, such as crack bridging, crack deflection, and microcracking. These mechanisms enable the enamel's microstructure to facilitate guided crack propagation and arrest, leading to significant toughening. The subsequent mean resistance-to-fracture parameters have been quantitatively determined: peripheral adamantine tissue (at the dental exterior) exhibits values of $(0.67 \pm 0.12) \text{ MPa} \cdot \text{m}^{0.5}$, while internal enamel demonstrates measurements of $(2.62 \pm 1.39) \text{ MPa} \cdot \text{m}^{0.5}/\text{mm}$ (with structural integrity enhancement progressively manifesting toward the amelodentinal junction), and at structural discontinuity presents values of $(2.07 \pm 0.22) \text{ MPa} \cdot \text{m}^{0.5}$.(40)

It has been explained that a material's brittleness is proportional to its hardness and elastic modulus, and inversely proportional to the square of its fracture toughness. Consequently, the elevated measurements of microhardness and elasticity coefficient proximal to the dental exterior may culminate in enhanced structural fragility of the peripheral adamantine tissue relative to the deeper mineralized substrate. (35)

2.2 Enamel Microcracks

2.2.1 Formation of Enamel Microcracks

A comprehensive examination of teeth with a powerful light during routine dental visits can frequently reveal microcracks in the enamel. These are known as enamel microcracks (EMCs), which usually do not extend past the dentin-enamel junction (DEJ) and do not show any loss or significant separation of the tooth structure. (43) These enamel microcracks (EMCs) are also categorized as incomplete tooth fractures (ITFs), defined as: "A fracture plane traversing the tooth structure, with unknown depth and orientation, not yet connected to the pulp and/or periodontal ligament, but which may progress to such a state." (43) The development of EMCs is generally attributed to irregularities in the maturation process, occlusal forces (such as those occurring during tooth wear and abrasion), traumatic injuries (like those experienced during tooth extraction), temperature fluctuations, and restorative procedures. (4,11,44) According to earlier studies, EMCs may become evident at the conclusion of orthodontic treatment, particularly after the removal of brackets. (5,6,11)

The understanding that the process of removing brackets results in the development of enamel microcracks (EMCs) prompts the inquiry: What causes enamel to fracture during debonding? As per suggestions outlined in a 1975 review article, a bond strength ranging from 5.9 to 7.9 MPa is considered adequate for the majority of clinical orthodontic scenarios. (45) However, the application of this "clinically acceptable" bond strength has been scrutinized, as it has not been proven whether this value is sufficient for in vitro bond strength applicable to clinical practice. (46) The average tensile strength of enamel was (10.3 ± 2.6) MPa. (47) When comparing the values between these two groups, it appears prudent to err on the side of caution during the debonding process. Additionally, the mean bond strength across various combinations of bracket types (metal or ceramic, with differing base designs and sizes), adhesives, and enamel conditioners (including types of etching materials and acid etching techniques) can vary from 5.6 to 17.0 MPa. (48,49) The literature may contain even greater bond strength figures of 20.2–30.7 MPa. (20,22) Therefore, the enamel surface fractures when the debonding force is greater than the enamel's tensile strength. (50)

Despite this, enamel fractures may occasionally occur at lower bond strength values, such as 9.7 MPa.(51) However, enamel damage has not been observed at bond strengths of 8.2 MPa or less.(45,46) The intensity of the debonding force is a significant factor in the occurrence of enamel damage.(46) At bond strengths of 11.9 MPa or lower, the risk of enamel damage has been demonstrated to be merely 5.0%.(46) Bond strengths exceeding 11.9 MPa were associated with a 21.0% risk of enamel damage, and this risk escalated to approximately 50.0% when bond strengths surpassed 14.7 MPa.(46)

While minor enamel microcracks (EMCs) do not initially lead to tooth fractures, their expansion over extended periods can be harmful, potentially leading to various pathological and adverse outcomes that might ultimately make the tooth irreparable.(47) Enamel cracks have been shown to be a permeable pathway that allows caries-producing bacteria access to the DEJ. (48) This means that caries lesions within the tooth can be detected without visible signs of caries on the surface. (48) In previously published literature, asymptomatic crack lines have been recognized as precursors to symptomatic cracked tooth syndrome. (47,49) The appearance of teeth can also be compromised by structural changes in the enamel.

The presence of enamel fractures, even when apparent, does not necessarily signify an incomplete coronal fracture or fractured tooth syndrome, as enamel cracks do not invariably extend into the dentin.(28) On the other hand, large fractures in the enamel can also occur in the absence of dentinal cracks.(28) Therefore, in determining the prognosis of teeth with EMCs, other variables need to be taken into account in the diagnostic process. These variables include the patient's age, the presence and location of wear facets, para-functional activity patterns, and the qualitative characteristics of the EMCs (severity, direction, and location in relation to occlusal loading and restorations).(28,50)

2.2.2 Characteristic of Enamel Microcracks

The orthodontic literature has extensively examined how the debonding process affects enamel degradation.(9,12,22) In some studies, the enamel surface has only been evaluated after the removal of brackets, and no attention has been paid to how the enamel looked before the bonding process.(10,51,52) On the other hand, because most studies included tooth surface analysis both before the bonding procedure and after bracket removal, it

was possible to evaluate undesirable changes in the enamel structure due to debonding.(9,12,20)

A systematic review of research conducted between January 2000 and July 2017 (5) revealed a growing scientific interest in enamel microcracks (EMCs) concerning bracket removal. These studies ranged from the qualitative and quantitative assessment of specific EMCs' characteristics to the distribution of crack frequency, (6,20) increased numbers and lengths of cracks(22) and changes in the frequency and severity of EMCs. (7,9,23,24)

In 1978, a measurement of the length of an EMC was attempted for the first time and published.(53) In order to calculate the length parameter, a known-size grid was superimposed on the photographic slide that was produced for each tooth that underwent the heat cycling process at different intervals.(53) Nevertheless, the study omitted information regarding the specific grid size and reference points chosen. A range of image processing programs, such as Adobe Photoshop CS (Adobe Systems Incorporated, San Jose, Calif., U.S.), (9,24,54) and Stereolith (Version 1, Shiraz, Iran)(24) were used in later published investigations to measure the length of EMCs both before and after debonding. A few investigations showed that the method may be used to do linear measurements for the length analysis of EMCs.(55) It has also been shown that the length of the EMC can be calculated by placing a ruler in the middle of the microscope lens both before and after the brackets are removed.(56) However, instructions on how to establish the initial and final length measurement points were not given, nor was it clarified how to obtain the exact same EMC before to and following the debonding process.(7–9,23,24) This is particularly important when EMC reverses course when passing through the buccal tooth surface. To ensure that the study is replicated, a thorough description of the methodology is required.

According to the literature review, the number of EMCs was typically calculated using image processing software and magnified images of the buccal tooth surface taken with laboratory equipment like a stereomicroscope fitted with a camera(7–9,22–24,55,57) or transillumination using a fiber optic light head .(12) To evaluate the variations in the quantity of EMCs, the evaluation process was conducted again both prior to and following debonding.

Taking the enlarged pictures of the buccal tooth surface, the direction parameter was analyzed.(7–9,24) In prior studies, the location of enamel microcracks (EMCs) relative to the tooth crown's longitudinal axis was fundamental to all proposed classifications of their directional characteristics, despite slight differences. The classification for the direction parameter was suggested as follows: horizontal (46–90° to the crown's long axis), oblique (31–45°), mixed (when EMCs altered direction), and vertical (0–30° to the crown's long axis).(9) Conversely, another study identified three directional characteristics for enamel microcracks: vertical (0–30° to the tooth's long axis), oblique (30–60° to the tooth's long axis), and horizontal (60–90° to the tooth's long axis).(8) At times, the direction parameter was only broadly classified (e.g., vertical, horizontal, and oblique) without a detailed explanation of the specific situations in which EMC would be categorized as vertical, horizontal, or oblique.(12) All of the aforementioned studies, however, do not provide information on how the same EMC was discovered prior to and following debonding.

The severity parameter was initially classified in a study that was published about 40 years ago.(11) The latter study proposed differentiating between pronounced enamel microcracks (PEMCs), which are visible to the naked eye under standard room lighting, and weak enamel microcracks (WEMCs), which are not visible under normal lighting but can be identified using a fiber optic light source.(11) The previously mentioned criterion for PEMCs was utilized to prevent a variety of borderline cases when additional light was used. This same classification for the severity characteristic or description of PEMCs was commonly applied in later published studies.(8,9,12,24)

2.2.3. Methods for Enamel Microcracks Evaluation

In the literature, a number of techniques for the identification of EMCs have been published, including staining, transillumination, ultrasonography, and OCT.(5,28,58) EMCs have previously been visualized using methylene blue dye, caries indicator, transillumination, and different techniques for hydrating and dehydrating tooth structure.(28) While transillumination was once the most widely used modality for diagnosing EMCs, there were a number of disadvantages to utilizing it without magnification. (28) Transillumination, in its first place, dramatizes all EMCs, making

them look as structural fissures regardless of their severity.(28) Second, subtle hue shifts become undetectable. Therefore, most studies that used the latter technique for EMCs investigation used transillumination with a fiberoptic light head to avoid the aforementioned problems.(11,12,20)

Nonetheless, it is well recognized that during force application techniques used in orthodontic therapy, certain modifications to the characteristics of EMCs take place.(3) A thorough quantitative examination of EMCs is necessary due to the likelihood for increased enamel damage to develop during debonding. A reliable strategy for studying fracture morphology is a replication technique that includes in vitro and in vivo testing.(59) As an alternate method, it has also been applied to the examination of non-carious cervical lesions (60) and the assessment of tooth surface loss. [6,28,97](4,29,30,61)

Numerous laboratory techniques (SEM, stereomicroscopy, COP, 3D scanning technologies) can be used to measure the depth of the lost enamel, or volumetric enamel loss, as well as to undertake spot or line measurements of the parameters of EMCs.(3,5,7–9,22,25–27,29,30) Table 1 presents the most widely used and well-established methods, together with their benefits and drawbacks, for analyzing the quantitative parameters of EMCs. Table1 displays pictures of EMCs captured using various approaches.

(3,5,26,27,29,62–65) Stereomicroscopy was used in most studies assessing EMCs in connection with the debonding process to visualize and analyze cracks.(6–9,22–24,57)

This was followed by transillumination using a fiber optic light head approach.(12,20)

Despite being frequently used for subjective surface observation (e.g., evaluation of surface roughness, identification of EMCs or other irregularities in tooth structure) after bracket removal, SEM technique has some advantages over stereomicroscopy, COP, and 3D scanning methods, like ultrasonography or CT scans, when it comes to evaluating EMCs (the advantages of SEM technique are listed in Table 1.(3)

Table 1 Comparison of methods for EMCs' characteristics evaluation

Stereomicroscopy; stereomicroscope (with camera)	Optical microscopy	Count, Orientation, Length, Position	Direct observation of EMCs requires no special sample preparation and is a non-destructive method.	Compared to scanning electron microscopy (SEM), this method offers lower resolution, with effective magnification reaching only 1000-2000 times. This limited magnification restricts the ability to measure the width of EMCs, and their depth cannot be assessed. Only a limited number of measurements can be performed per tooth surface, making it difficult to analyze uneven surfaces. Additionally, the process is time-consuming and suitable only for in vitro measurements.
SEM; SEM	Electron microscopy	Count, Orientation, Length, Position, Width	Direct evaluation and measurement of EMCs can be achieved with superior resolution, exceeding 1 nm, and magnification capabilities up to 2 million times. This allows for the visualization of structures not discernible with optical microscopy and provides a three-dimensional view of an object's external form. The method is non-destructive and highly sensitive.	This method requires sample preparation, although coating teeth with a conductive layer is not necessary for evaluating enamel microcracks (EMCs). It offers surface lateral characterization in 2D, but does not allow for measuring the depth of EMCs. The number of measurements per tooth surface is limited, and analyzing non-flat surfaces can be challenging. Additionally, the process is time-consuming and is conducted in vitro.
COP; confocal optical profilometer	Optical microscopy	Count, Orientation, Length, Position, Width, Depth	Direct assessment and measurement of enamel microcracks (EMCs) using this technique offers both lateral and axial (3D) surface characterization. It requires no special sample preparation and is a non-destructive, highly sensitive method.	This method allows for limited measurements per tooth surface but is more sensitive to non-flat surfaces compared to SEM. It is a time-intensive process and is conducted in vitro.
OCT; optical coherence tomographer	Low-coherence interferometry	Count, Orientation, Length, Position, Enamel loss (volume), Depth	This technique offers real-time imaging with high spatial resolution, achieving axial resolution of a few micrometers. It enables precise and repeatable measurement of numerous points (up to 50,000) on tooth surfaces and allows for volumetric calculations of total substance loss through 3D imaging. It is a non-destructive, non-radiative method and is time efficient.	This method involves indirect measurement through a replication procedure, as the tooth surface can cause laser beam scattering and resolution loss. It has limited penetration depth and scanning range but can be used for both in vivo and in vitro measurements.
Ultrasound	High frequency sound waves	Count, Orientation, Length, Position, Enamel loss (volume), Depth	Real-time imaging. High resolution. Precise technique. Non-destructive, non-radiative method. Time-efficient process.	Sample preparation (selection of suitable coupling media for tooth enamel). Sensitive to non-flat surfaces. In vivo and in vitro measurements.

2.3 Brackets

Orthodontic braces are tools designed to adjust and align teeth, enhancing both occlusion and overall dental health. While the ultimate goal for patients undergoing orthodontic treatment is to achieve an aesthetically pleasing smile, their appearance during the process is also a significant concern. In response, manufacturers have developed various solutions, such as lingual or "invisible" braces, reduced-size metal brackets, plastic brackets, and transparent ceramic brackets. Initially introduced in the early 1970s, plastic brackets were marketed as a more visually appealing alternative to metal ones. However, they quickly fell out of favor due to issues like discoloration and slot deformation caused by water absorption.(66,67) Because of this, producers changed the plastic brackets by adding ceramic and metal filling to strengthen the slots.(68) The first brackets in orthodontics were created using polycrystalline ceramic and monocrystalline sapphire materials in the middle of the 1980s.(68,69) Ceramic brackets were initially introduced as an aesthetically pleasing option that resisted staining and could withstand most orthodontic forces, unlike their plastic counterparts. However, they had notable limitations, including the inability to form chemical bonds with resin adhesives, reduced fracture toughness, and heightened frictional resistance between metal arch wires and ceramic bracket.(68,70,71)

2.3.1. Ceramic Bracket Types and Composition

Ceramics brackets a wide range of materials composed of metal oxides and non-metallic elements, including glass, clay, gemstones, and various ceramic compound blends. (72) Ceramics are fundamentally distinct from polymers and metals, utilizing diverse atomic structures. Modern ceramic engineering has leveraged these characteristics to develop innovative ceramic materials with a broad spectrum of applications.(73) Alumina (Al_2O_3) is a common component of contemporary ceramics and is created when steel is treated with aluminum to eliminate dissolved oxygen.(73–75) Alumina can be utilized as a polycrystalline or single-crystal substance. Orthodontic ceramic brackets are made from both monocrystalline and polycrystalline alumina.(76)

The majority of ceramic brackets available today are composed primarily of aluminum oxide. There are two main types: polycrystalline ceramic brackets and monocrystalline ceramic brackets, which differ significantly in their manufacturing processes.(77,78) Polycrystalline brackets are currently more widely accessible due to their simpler fabrication process.(76) The most noticeable difference between polycrystalline and single crystal brackets lies in their optical clarity. Single crystal brackets are transparent, offering significantly greater clarity compared to polycrystalline brackets.(76–78)

Table 2 Ceramic Bracket Types and Composition

Brand	Material	Prescription	Slot Size	Additional Features
3M™ Clarity™ Advanced	Ceramic	MBT™, High Torque	0.018", 0.022"	Offers aesthetic appearance, durability, and low friction properties.
Symetri Clear™	Transparent Ceramic	Standard and Customizable	Optimized	Aesthetic twin design with optimized in/out dimensions, providing high durability.
Inspire ICE™	Monocrystalline Sapphire	Standard	0.018", 0.022"	Completely transparent, stain-resistant, and superior aesthetic design.
Avair SL	Polycrystalline Ceramic	Damon Compatible	0.018", 0.022"	Self-ligating, low friction, and offers high comfort.
DENTAURUM Discovery®	Polycrystalline Ceramic	Standard	0.022"	Metal slot for enhanced durability, providing aesthetic and precise alignment.
Radiance Plus®	Monocrystalline Ceramic	Standard	0.018", 0.022"	Superior transparency, durable, and an aesthetic twin bracket.
Polycrystalline Bracket	Polycrystalline Ceramic	Standard	0.018", 0.022"	Durable structure, suitable for clinical use with low friction properties. Clinical use with low friction properties.
Polycrystalline with Palladium Gold Insert	Polycrystalline Ceramic + Palladium Gold Alloy	Standard	0.018", 0.022"	Enhanced durability with metal insert, providing aesthetic and precise alignment.

2.3.2. Properties of Ceramic Brackets

2.3.2.1. Hardness

Resilience is a well-known attribute of ceramic brackets. Compared to enamel, they are noticeably tougher. (14,79) Therefore, it is imperative to prevent any contact between ceramic brackets and enamel. Serious enamel damage may result from this kind of contact.(78)

2.3.2.2. Tensile Strength

The maximum stress a material can withstand when being stretched or pulled before it fails or breaks is referred to as the ultimate tensile strength, often simply called tensile strength.(80) Because of its hard atomic structure, ceramic materials are nearly impossible to redistribute and relieve while under stress.(76) Metals and polymers are examples of ductile materials that undergo plastic deformation prior to failure.(79) In other terms, stainless steel exhibits elongation of around 20% at failure (ductile fracture), whereas ceramics exhibit elongation of less than 1% at failure (brittle fracture).(81) Consequently, ceramic brackets do not flex, indicating that they are significantly more susceptible to breaking under similar conditions compared to metal brackets.(81)

2.3.2.3. Fracture Toughness

Fracture toughness refers to a material's ability to resist fracturing despite having a crack(83) Due to the inevitability of minor imperfections such as scratches, fractures, voids, and holes during material production, fracture toughness becomes a critical property. The impact of these microscopic flaws on the material depends on several factors, including the material's fracture toughness, the level of stress, crack length, resistance to crack propagation, and environmental conditions.(82)

It is more difficult for a crack to spread through a material with a greater fracture toughness.(83) Compared to monocrystalline alumina brackets, polycrystalline alumina brackets have a greater fracture toughness.(83) Because cracks interact with grain boundaries (GBs), polycrystalline brackets are more resistant to fracture propagation. A GB is the interface of a polycrystalline (many crystal) material between two "grains" (crystals). These GBs are where cracks are inhibited.(81)

2.3.2.4. Friction

Upon comparing polycrystalline and monocrystalline ceramics, it was determined that the former had a greater coefficient of friction.(14) Consequently, metal inserts were incorporated into the arch wire slots of polycrystalline ceramic brackets to address this issue.(84) However, it was noted that the metal insert's sharp edges can "dig into" the softer arch wire material, increasing resistance to sliding and decreasing tooth movement efficiency.(77,85) The addition of roughness to the polycrystalline ceramic bracket slot's floor was another change. However, the frictional resistance was not decreased by these bumps.(86)

2.3.2.5. Base Characteristics

In order to attach ceramic bracket bases to the adhesive, a number of retention mechanisms were created. These include mechanical retention, chemical retention, and a mix of both of them.(87,88) The chemical retention method was the initial technique developed for bonding ceramic brackets. This now-obsolete method involved applying a glass coating to the flat base of the ceramic bracket and using a silane coupler to establish a chemical bond between the adhesive and the glass-coated bracket base. The bifunctional nature of the silane molecule allowed one end to react with the adhesive and the other end with the glass coating on the bracket base.(19,81) Throughout the bracket removal procedure, researchers noted that the adhesive chemical bonding system created unusually robust attachments, resulting in structural compromise to the dental exterior, manifested as microfractures and enamel fragment detachment.(6,14,19,87,89,89)

Recent innovations in ceramic attachment foundation engineering have emerged, utilizing aluminum oxide polycrystalline structures featuring textured bases composed of either spherical vitreous elements or irregularly oriented crystalline projections. These attachment systems provide exclusively mechanical interdigitation with the orthodontic bonding agent.(90)

Multiple mechanical foundation configurations are currently accessible in the market, encompassing nodular structured base architectures, spherical foundation designs with cervical element reduction, convergent-divergent base patterns, laser-modified surface

configurations, crystalline microstructure foundations with stress-directing features, and aperture-based bonding interface designs.(14,91)

2.4. Bonding Procedure

There are two main types of bonding procedures: traditional, which involves covering both the etching and rinsing phases, and self-etch, which combines the etching and priming steps into one step and does not require rinsing.(46,51) It has been shown that self-etching primers can achieve lower, yet clinically sufficient bond strength(46,51) while causing less enamel damage, making them more conservative compared to the conventional system.(46,65,92)

2.4.1. Bonding Ceramic Brackets

Ceramic bracket bonding brings questions. In the beginning, research has demonstrated that the physical features of ceramics may cause unfavorable and permanent alterations in the tooth structure during the debonding process.(1,12,93,94)Second, choosing the correct kind of bond such as ceramic brackets with chemical or mechanical retention is essential to avoiding or significantly reducing the chance of EMCs occurring while removing the brackets.(6,22) Consequently, comprehensive knowledge regarding the material properties and architectural composition of ceramic orthodontic attachments may contribute to minimizing or eliminating the heightened potential for adamantine tissue compromise associated with the removal process of these particular attachment systems.

The main component in every ceramic bracket on the market right now is aluminum oxide (Al_2O_3). (91,95,96) This compound demonstrates significant bond strength, resilience to thermal and chemical variations, compatibility with biological systems, and favorable aesthetic properties.(76,79,89,96,97) It is possible to distinguish between two types of ceramic brackets: monocrystalline and polycrystalline, based on the changes that occur throughout the production process.(76,91,97) Optical clarity is the most obvious

distinction between these two varieties of ceramic brackets, with monocrystalline brackets being notably clearer and more transparent.(91)

Alterations in enamel structure during the debonding process are intrinsically linked to the physical characteristics of ceramics, which stem from their atomic bonding. These attributes include hardness, tensile strength, and fracture toughness or brittleness.(91,95) One notable physical property that provides ceramic brackets an advantage over stainless steel counterparts is the exceptionally high strength of aluminum oxide.(77,91,95) It is crucial to highlight that ceramic brackets possess a hardness that is nine times greater than that of stainless steel brackets or enamel. (76) Therefore, significant enamel abrasion might happen very fast in the event that teeth and ceramic braces come into contact. (78,91,98)

Tensile strength, defined as the ability to withstand structural failure, is markedly greater in monocrystalline alumina compared to polycrystalline alumina, yet polycrystalline alumina surpasses stainless steel in this regard.(76,77,95) This characteristic of ceramics is dependent on the condition of the ceramic surface (76,82,99).Therefore, the stress necessary for ceramic bracket fracture can be greatly decreased by even the slightest surface flaws or fractures.(12,91,95) This particular physical attribute renders ceramic brackets less durable, resulting in minor deformation of less than 1.0% .(76,82,91,99) Fracture toughness, a key metric of a material's ability to withstand fracturing, is another vital physical property of ceramics in orthodontics. It is 20 to 40 times lower than that of stainless steel.(76,82)Because of this, ceramic brackets are more prone to break during the debonding process and are far more easily fractured than metal brackets. When it comes to ceramic brackets, polycrystalline ones are more fracture-tough than monocrystalline ones.(3,100) Enamel has a lesser fracture toughness than ceramic brackets(91), and ceramic brackets bonded to brittle, hard enamel are less able to withstand force.(76) Therefore, several research on the evaluation of enamel damage after ceramic bracket removal attest to the fact that this is a pertinent concern for doctors.(12,67,77)

Choosing the best kind of bond is another crucial clinical consideration for ceramic brackets. Chemical retention, mechanical retention, and a mixture of the two are the three distinct bonding methods for ceramic brackets.(12,88,96) Silane-treated chemically

retentive bases, where a silane crosslink serves as a chemical intermediary between the adhesive resin and the bracket base, are utilized to achieve chemical retention.(22,96,101) Undercuts, grooves, or indentations in the bracket base that permit mechanical interlocking with the adhesive. can offer mechanical retention.(6,96,101) To facilitate mechanical retention, manufacturers are introducing diverse ceramic bracket base designs, including buttons, mechanical balls, micro-crystalline, and polymeric bases, wherein the enamel adheres to the polymer instead of the ceramic.(6,96)

According to studies, chemically maintained ceramic brackets have a strong bond that might cause enamel damage when they debond.(6,8,67,88,102) The distribution of stress concentration over the bonding surfaces may account for the variation in bond strength between ceramic brackets that are mechanically and chemically maintained.(91) When mechanical retention occurs, the adhesive fails brittly due to large localized stress concentrations at the sharp edges of the grooves or other retention sites built into the bracket's base.(91,97) In contrast, chemical retention involves no localized stress zones and a considerably larger dispersion of stress throughout the whole adhesive surface.(91,97) Therefore, debonding and pure adhesive failure require a significantly higher shear bond.(91,99) The groups employing mechanical retention and polymer base brackets showed no statistically significant differences in enamel damage when assessing the impact of various ceramic bracket bonding mechanisms on the enamel surface, including effects on potential increases or formation of new EMCs.(6) Nevertheless, statistically significant enamel damage was caused by the debonding process of chemically preserved ceramic brackets. (6) A subsequent study's findings indicated that using pliers to debond chemically bonded ceramic brackets poses a substantial risk of enamel damage, evidenced by the greatest increase in both the number and length of EMCs.(56) Sources indicate that the removal of ceramic brackets does not elevate the risk of enamel damage compared to metal brackets, as there is no statistically significant difference in the number or length of enamel microcracks (EMCs) following the debonding of metal brackets, ceramic brackets with mechanical retention, or ceramic brackets with chemical retention, all removed using sharp-edged pliers.(22) A thorough analysis of in vitro research on the evaluation of EMCs' properties before and after debonding identified a number of factors (such as various retention strategies and debonding techniques) that could be responsible for the discrepancy in the previously described outcomes.(5)

2.5. Debonding Procedure

Debonding typically refers to the removal of orthodontic brackets and residual adhesives from tooth enamel at the end of fixed appliance treatments. Ceramic brackets are characterized by a lack of elasticity.(16) The rigid nature of ceramic and enamel results in limited ability to absorb stress when exposed to debracketing forces at the end of treatment. As a result, bracket breakage and/or enamel damage may occur during the debracketing process.(76,81) Several strategies are available to reduce the negative impacts associated with the debracketing of ceramic brackets. These techniques include traditional mechanical methods, as well as ultrasonic, electrothermal, and laser approaches. (81,87)

While the mechanical bracket removal technique makes it nearly impossible to regulate and standardize the actual debonding pressures, it is probable that this debonding pattern would mitigate forces above that typically seen in clinical practice during manual bracket removal.(10) The manual removal of brackets with appropriate pliers applies a bilateral force at the interface between the bracket base and adhesive, ensuring that most of the adhesive remains on the enamel surface. This debonding pattern is suggested to protect the enamel surface.(51,103)

Manufacturers of ceramic brackets consistently offer guidelines for the effective debonding of their brackets, including recommendations for the selection and positioning of pliers, as well as the method of force application. Consequently, most in vitro research on EMCs post-removal of ceramic brackets were conducted in alignment with these references: Weingart pliers were utilized for chemical applications involving torsional rotational force; Fascination, Fascination 2; Dentaaurum, Inspringen, Germany. Retention brackets included (6–8) mechanical (squeezing force; APC Plus Clarity; 3M Unitek),(12) Howe pliers for mechanical retention brackets (squeezing force; Clarity; 3M Unitek), (6) orthodontic wire cutter for mechanical retention with polymer base brackets (squeezing force; InVu; TP Orthodontics, LaPorte, Ind., U.S.), (6) specific plastic debonding pliers for mechanical retention brackets (peeling force; Inspire Ice;Ormco, Orange, Calif.,

U.S.), and a debonding instrument for mechanical retention brackets (squeezing force; Clarity; 3M Unitek).(12)

2.5.1. Mechanical Debonding

Three mechanical debonding techniques have been identified, encompassing lift-off, twisting, and delamination.(104) The initial method employs a lift-off debracketing instrument (LODI). The pistol-grip plier is placed over the bracket, applying a debonding force to the bracket's tie-wings. LODI is unsuitable for ceramic brackets because of their fragility.(2) The wrenching technique utilizes a specialized instrument that applies a wrenching or torsional force at the base of the bracket.(104)

The delamination approach was the first method developed and continues to be the most widely recommended technique for removing ceramic brackets.(81,91) This technique involves applying a gradual compressive force with the sharp blades of the debracketing pliers, positioned on the enamel surface and within the adhesive, thereby creating a wedging effect.(85)

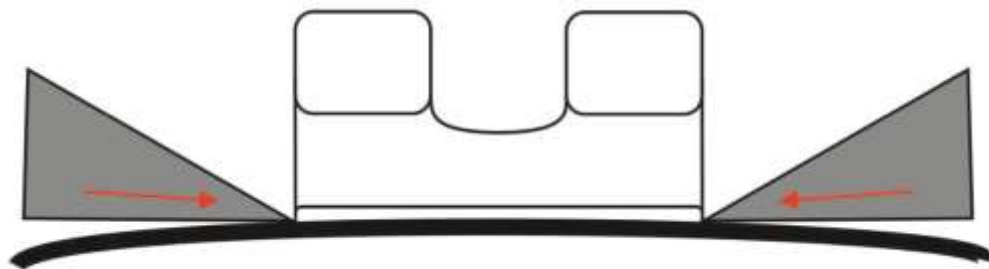


Figure 1 Schematic Presentation of The Delamination Technique

A force produced by slow, progressive compression seems to offer the best chance for initiating crack propagation within the adhesive, leading to cohesive failure and thereby minimizing the risk of enamel damage and bracket fracture. Cohesive bond failure occurs within a single material and is characterized by cohesive forces among identical atomic species.(76,81,87,104)

In 1993, Bishara and Fehr(105) evaluated the mechanical pressure applied by instruments with varying contact surfaces during ceramic attachment removal from human posterior maxillary dentition. The expanded instrument edges measured 3.2 mm in width, whereas the reduced-width edges measured 2 mm. Aluminum oxide polycrystalline orthodontic attachments employing dual retention mechanisms-physical interdigitation and chemical adhesion-were utilized in the investigation. The findings from this laboratory-based research indicated that the reduced-width instrument edges generated a substantially lower average detachment force of 120 kg/cm² in comparison to the expanded contact surfaces, which demonstrated a measurement of 150 kg/cm². Bishara and Fehr(105) established that a significant decrease (20%) in attachment removal force reduces mechanical stress on the dental exterior, consequently minimizing the potential for adamantine tissue compromise. Research has documented and highlighted that forces exceeding 138 kg/cm² or 13.53 MPa during attachment removal procedures should be avoided.(15,45,81)

In 2000, Arici and Minors(106) conducted an in vitro investigation employing four distinct ways of debracketing. They indicated that minimizing the contact area between the plier blades and the glue decreases the force required to commence the removal of ceramic brackets. Visual examination without magnification revealed no evidence of adamantine tissue compromise or attachment structural failure. Arici and Minors(106) utilized extracted bovine anterior mandibular dentition and aluminum oxide polycrystalline orthodontic attachments incorporating chemical adhesion mechanisms. Their investigation determined that their findings substantially corroborate the determinations presented by Bishara and Fehr. (105)

Since the introduction of ceramic brackets over 30 years ago, significant issues during debonding have been observed.(14,77,81,93,95,107) Ensuing laboratory-based research endeavors sought to enable the creation of more reliable and clinically appropriate aluminum oxide orthodontic brackets. The primary aim of these scientific inquiries was to reduce the mechanical forces required during ceramic brackets removal, thereby preserving both adamantine tissue and attachment structural integrity.(15,81,105,106)

2.5.1.1. Precautions for Mechanical Debonding

Clinical prudence suggests avoiding the application of aluminum oxide orthodontic attachments to structurally compromised dentition, including fragile, devitalized elements (those having undergone endodontic intervention), teeth exhibiting developmental irregularities, regions of mineral-depleted enamel, adamantine microfractures, or substantial restorative interventions, when alternative options exist. Such compromised dental structures demonstrate elevated susceptibility to adamantine tissue damage relative to intact dentition during mechanical attachment removal procedures.(2,87) Precaution must also be used with porcelain restorations, including crowns and veneers.(107) Peripheral adhesive excess must be eliminated utilizing a dental explorer prior to polymerization or with rotary instruments following polymerization during the bonding procedure. Meticulous removal of extraneous bonding material enables complete adaptation of the precision-edged instrument components against the adamantine surface during ceramic bracket removal. This approach ensures appropriate force distribution and fracture propagation through the bonding interface, promoting cohesive failure within the adhesive medium, thereby preserving both the dental surface and bracket structural integrity.(76,81,87)

Unfortunately, debonding procedures occasionally result in structural failure of the brackets. Fragmented components may either separate completely (unattached segments) or maintain adhesion to the dental exterior. Mechanical reduction of attachment fragments, regardless of rotational velocity, without appropriate thermal regulation via water irrigation, may induce permanent damage and devitalization of the dental pulpal tissues.(51) Consequently, water cooling is essential during the grinding or removal of ceramic bracket fragments.(108,109) Additionally, the utilization of enhanced evacuation systems in proximity to the reduction zone has been emphasized to minimize the dissemination of aluminum oxide particulate matter.(81,109) These microscopic elements have been reported to precipitate conjunctival inflammation and cutaneous discomfort of the upper extremities.(109)

Bishara and Fehr(87) advocated for the substitution of instrument cutting surfaces following the removal of 50 orthodontic attachments when mechanical devices are employed for detachment procedures.(87) Instruments with permanent cutting elements

necessitate periodic edge refinement. Precision-edged instrument surfaces are critical for atraumatic attachment removal, particularly for facilitating fracture propagation within the bonding medium rather than the adamantine tissue or aluminum oxide attachment. The specialist practitioner should not delegate the removal of ceramic orthodontic attachments to supporting clinical personnel.(87,110)

2.5.1.2 Proposed Adjunctive Methods for Mechanical Debonding

Larmour and Chadwick(111) evaluated the effectiveness of a proprietary adhesive dissolution compound, post-detachment formulation (P-de-A) (Oradent Ltd., Eton, Berks, UK). This emerald-colored semisolid preparation, containing mentha piperita oil derivatives, was claimed to facilitate ceramic attachment removal and subsequent adhesive remnant elimination. The manufacturer of P-de-A suggested application periods of 60-120 seconds to reduce resin cohesion. However, the experimental outcomes from the P-de-A investigation failed to substantiate these manufacturer assertions.(111,112)

In 1997, Arici et al.(113,114) proposed the utilization of a compressible microporous ceramic interface to facilitate bracket removal. These porous structures were bonded to the attachment substrate utilizing polymerizable resin. Subsequently, these integrated attachment/interface assemblies were adhered to the adamantine surfaces of experimental bovine anterior dentition. The authors (114) of this laboratory-based research documented the atraumatic removal of these ceramic attachment/interface configurations, with no structural failures of the ceramic components or any evidence of adamantine tissue compromise observed.

2.5.1.3 Ultrasonic Debonding

The ultrasonic debonding process employs specifically engineered tips to generate vibrations at the bracket-adhesive contact, facilitating the erosion of the adhesive layer between the enamel surface and the bracket base.(19) The ultrasonic debonding process was initially devised for the removal of cast metal and bridge retainers.(115) Boyer et al.(116) (2018) employed an ultrasonic chisel tip from Cavitron and a universal testing machine to shear ceramic brackets glued to excised human incisors and canines. The

degree of polymerization of the light-activated adhesive was systematically altered by varying the exposure times to the curing light. The study found that the ultrasonic chisel significantly reduced the force required to detach the brackets. The average debonding time was approximately 16.6 seconds, and the researchers noted that this debonding method is not recommended without further refinement.

Chen et al.(117) investigated the influence of ultrasonic precrack preparation on debonding force and failure mechanisms in the debonding of ceramic brackets. Eighty excised human premolars were categorized into four groups: Inspire, precrack Inspire, Clarity, and precrack Clarity, with each group including 20 teeth. Preparations prior to cracking were conducted at the mesial gingival line angle of Inspire brackets and on the mesial aspect of Clarity brackets using an ultrasonic tip. The debonding force, failure mechanisms, and bracket fracture score were quantified and assessed. The findings indicated that ultrasonic precrack preparation markedly reduced the average debonding force, with no enamel damage observed post debonding. The research determined that ultrasonic precrack preparation can markedly reduce the debonding force and facilitate bracket debonding along an optimal fracture plane, preserving both the bracket and the enamel from trauma.

2.5.1.4. Electrothermal Debonding

In 1986, Sheridan et al.(118) initially described thermoelectric detachment methodology (TDM) for the removal of metallic orthodontic attachments. Application with aluminum oxide attachments has been reported to reduce the incidence of structural failures during TDM. The decreased frequency of attachment fracture is attributed to the minimal force necessary to disrupt the interface following thermal application, which promotes adhesive failure through thermal modification or structural weakening of the bonding substrate. A minimal detachment interval per attachment (2 ± 1 s) was reported. The possibility of pulpal tissue injury has been acknowledged. Fortunately, no evidence of permanent pulpal compromise was detected with electrical vitality assessment.(119–121)

2.5.1.5. Laser Debonding

Various laser types have been employed for the debonding of ceramic brackets.(54) Examples encompass carbon dioxide (CO₂) laser (122), neodymium-doped yttrium-aluminium garnet (Nd:YAG)(123), diode laser (124), erbium and chromium-doped yttrium, scandium, gallium garnet (Er,Cr:YSGG) (125), and erbium-doped yttrium aluminum garnet (Er:YAG).(126) This appears to closely resemble ETD; but, with laser-assisted debonding, the thermal energy imparted to the ceramic bracket may be meticulously regulated, thus mitigating the risk of overheating.(87,127) The duration for the removal of ceramic brackets using the laser-based approach is 1 to 5 seconds. Debonding forces are markedly diminished with lasers.(54,128) Consequently, the chances of enamel degradation and bracket fracture are markedly diminished. The elevated expense of this equipment may provide a drawback for the orthodontist.(87)

2.6. Removing of Remaining Adhesive

The concluding phase of fixed orthodontic treatment, entailing the extraction of brackets from the tooth surface, carries a significant danger of inducing irreversible damage to the tooth surface if executed without precision and caution.(129) The loss of enamel and the ensuing exposure of enamel prisms to the oral cavity diminish enamel's resistance to organic acids found in dental plaque, hence elevating the risk of demineralization.(98) The removal of brackets is associated with heightened enamel surface roughness, greater susceptibility to demineralization, and the potential for colour alteration.(130) Residual adhesive and composite resin remains following orthodontic bracket debonding may result in bacterial plaque accumulation, the onset of periodontal disease, porcelain discolouration, and diminished aesthetics.(131)

Methods for removing adhesive remnants include:

- Tungsten carbide bur with a high-speed handpiece.(132)
- Tungsten carbide bur with a contra-angle handpiece at high or low speed.(132)
- Carbide bur combined with Sof-Lex discs using high or low-speed handpieces.(133)
- Air abrasion with aluminum oxide.(134)

Evidence indicates that traditional adhesive removal techniques can induce noticeable roughness on the enamel surface, generate deep gouges of 10-20 μm in depth, and lead to a loss exceeding 100 μm of the underlying enamel.(135) In addition to traditional techniques, fiber-reinforced composite burs have been proposed for the elimination of adhesive residues.(130,136,137)

Prior research established that rotational speed is a critical variable, since the employment of a tungsten carbide bur with a low-speed handpiece resulted in less damage compared to a high-speed handpiece, which exhibited the poorest performance.(137,138)

Recently, ultraviolet (UV) fluorescent compounds have been included into orthodontic adhesives to facilitate the removal of adhesive remnants; however, employing this method with multiblade tungsten-carbide burs did not result in reduced damage compared to conventional illumination.(139)

3. HYPOTHESES OF STUDY

Null Hypothesis (H_0): There is no statistically significant difference among various debonding techniques in terms of the length and characteristics of enamel microcracks following ceramic bracket removal.

Alternative Hypothesis (H_1): There is a statistically significant difference among various debonding techniques in terms of the length and characteristics of enamel microcracks following ceramic bracket removal; certain debonding techniques cause less damage to the enamel surface compared to others.



4. MATERIALS AND METHODS

4.1. Characteristics of Enamel Microcracks Before and After Debonding of Ceramic Brackets

4.1.1. Teeth Selection

Sixty extracted bovine teeth were used for this study. Prior research has demonstrated that bovine enamel and human enamel reveal similarities in their physical qualities, composition, and adhesive binding strength.(140–143) The primary criteria for the selection of teeth were as follows: (1) intact buccal enamel, (2)no white spots,(3)no signs of enamel hypoplasia, (4) no visible EMC's. Prior to initiating the investigation, a power analysis was conducted to determine the sample size.(144) Due to the absence of a standardized approach for sample size determination in in vitro investigations, the sample size was determined using a formula derived from previously published study:(145)

4.1.2. Sample Preparation

The teeth were submerged for seven days in a 0.1% thymol-water solution at room temperature to ensure asepsis and prevent dehydration. Subsequent to this interval, the residual soft tissues, calculi, and bone pieces attached to the roots were excised.(146)

4.1.3. Initial Examination of the Enamel Surface Utilizing Scanning Electron Microscope

The buccal enamel surfaces of all teeth in the study were analyzed using a scanning electron microscope (Electron Microscope EVO® 40 Series (Carl Zeiss AG, Germany)) linked to a computer for image acquisition, as illustrated in Figure Xxx . The SEM was operated at 15 kV, $< 5 \times 10^{-2}$ Pa (electron gun vacuum) and at $\approx 30 - 50$ Pa (specimen chamber vacuum). The suitable and uniform positioning of each tooth for the scanning method was established. The highest resolution and contrast images were achieved when

the distance to the SEM detector was ideal, specifically at 1 mm below the entrance to the sample observation chamber.



Figure 2. Electron Microscope EVO® 40 Series (Carl Zeiss AG, Germany)

The teeth lacked a conductive coating before the SEM analysis. The preliminary assessment of EMCs was conducted at magnifications of $\times 50$ – 100 . The determination of ideal magnification for each tooth was contingent upon the height of the tooth's crown and the morphology of the enamel surface. This adaption of the magnification magnitude facilitated the reconstruction of the buccal tooth surface using a comparable number of micrographs for all teeth. All teeth were examined using a scanning electron microscope (SEM) at $\times 50$ – 100 magnification. If there was any doubt regarding the presence of a crack, the area was analyzed at a higher magnification for confirmation. Since all the teeth used in the study already had pre-existing cracks, no additional evaluation was conducted for teeth without enamel microcracks (EMCs). The entire scanning procedure was performed by experienced operators following a standardized protocol. To ensure measurement consistency, all teeth were examined under identical working conditions by a single operator.

A detailed evaluation of the buccal tooth surface and a further examination of enamel microcracks (EMCs) are presented in Figure 3. SEM micrographs of the buccal enamel surfaces of all teeth were captured. To ensure precise examination, the areas where cracks would be analyzed were framed using paper tape, and reference points were taken from these marked regions.

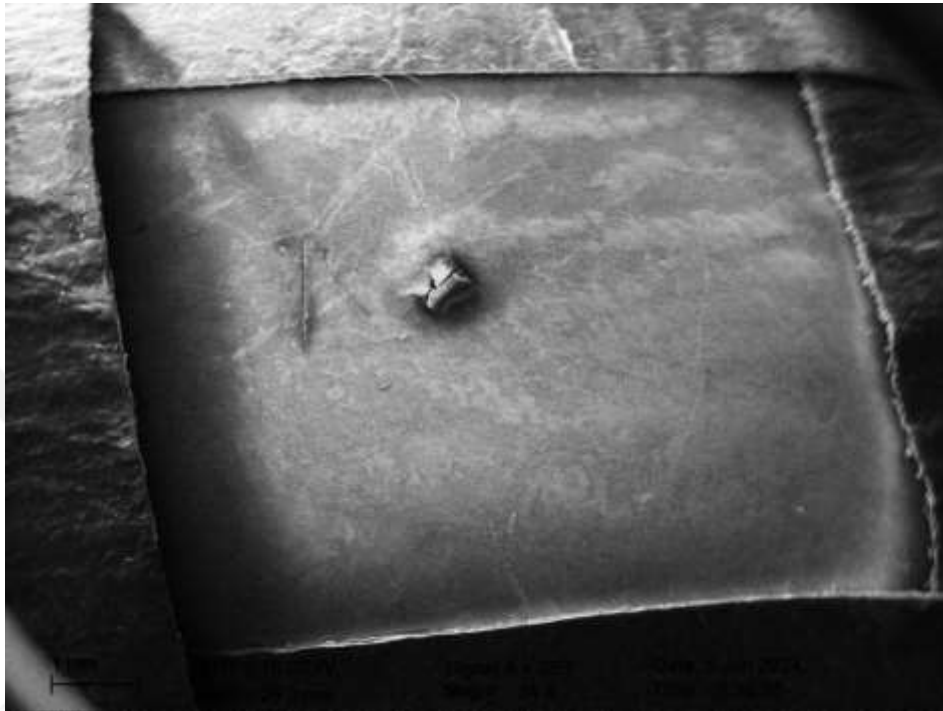


Figure 3 .SEM Image Before Bonding

Prior to SEM imaging, the teeth were categorized into five groups according to the direction of bracket removal. The categorization occurred before the imaging procedure to guarantee a systematic assessment. Each tooth received a distinct number, and the assignment was conducted randomly through a lottery system. The numbers were placed in a bowl, meticulously mixed, and subsequently selected at random by the examiner to categorize the teeth into their various groups. This strategy guaranteed an impartial allocation of samples among the experimental conditions.

Using a digitally sketched ruler, each tooth was divided into 10 measurement areas (MAs) within its designated region, resulting in a total of 30 MAs per tooth. The SEM measurement scale was used to measure the distance between two MAs. For each tooth, one EMC was analyzed in detail. If multiple EMCs were visualized, the longest EMC was selected for analysis. The qualitative and quantitative characteristics of the longest

EMC, including severity, direction, location, length, and width, were examined before and after debonding for all teeth.

The orientation of EMC was categorized as: vertical (0–30° relative to the longitudinal axis of the crown), oblique (31–45° relative to the longitudinal axis of the crown), horizontal (46–90° relative to the longitudinal axis of the crown), and mixed (when EMC alters its orientation while extending across the buccal tooth surface).(9)

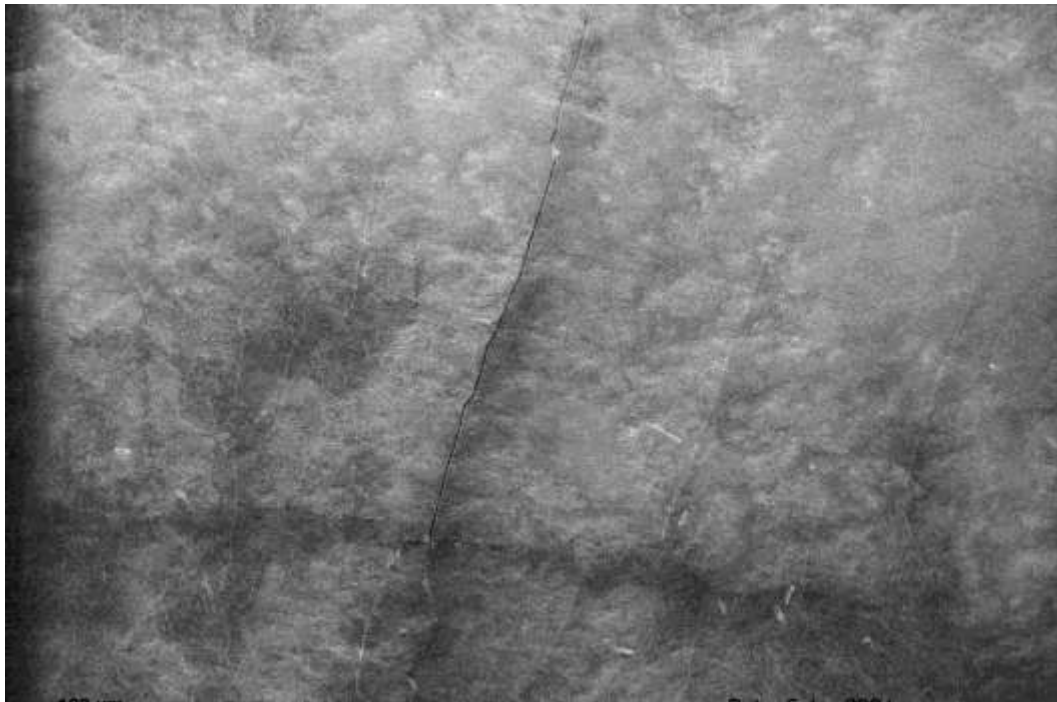


Figure 4. Vertical (0–30° Relative To The Longitudinal Axis Of The Crown)

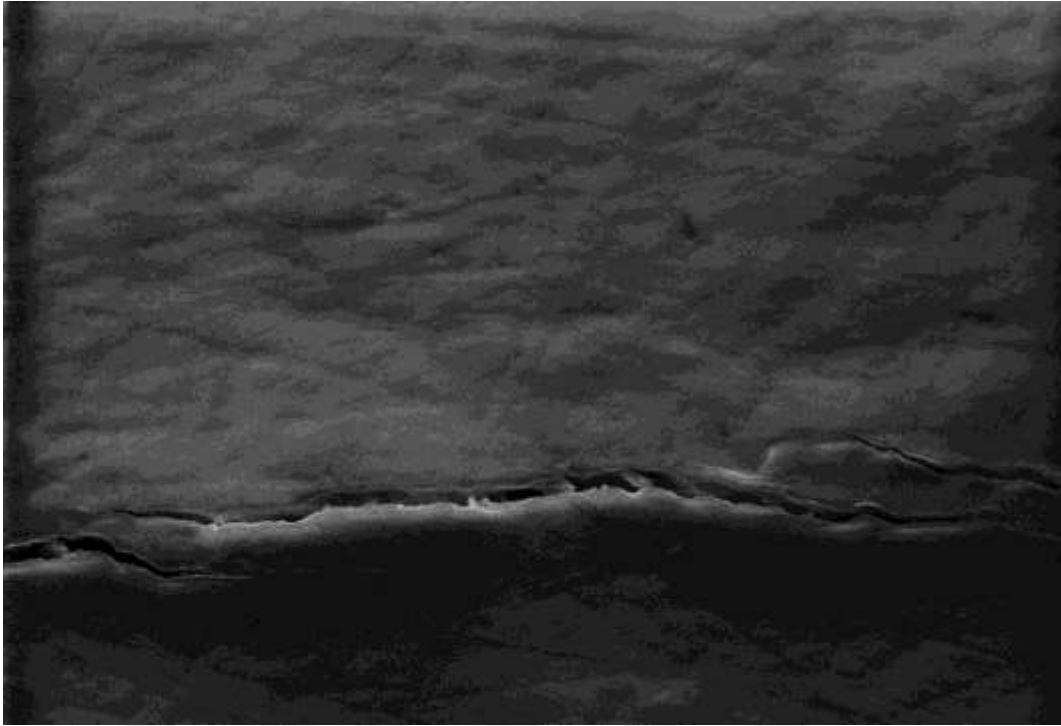


Figure 5. Horizontal (46–90° Relative To The Longitudinal Axis Of The Crown)

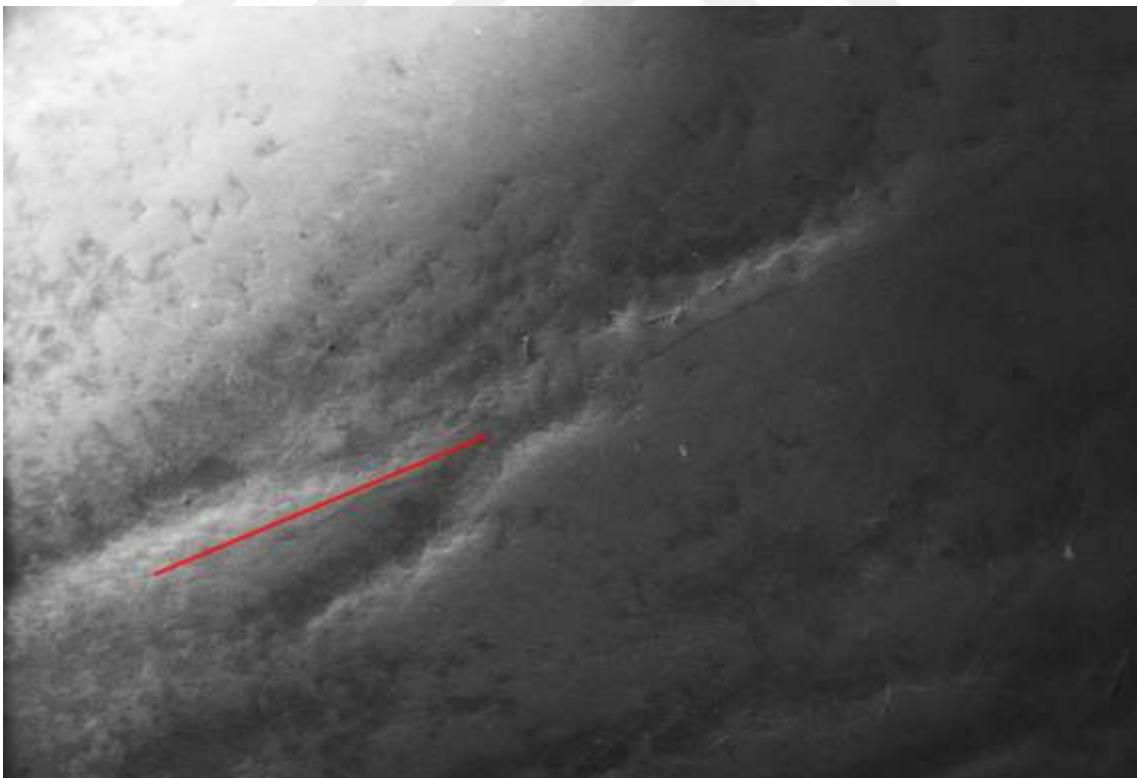


Figure 6. Oblique (31–45° Relative to The Longitudinal Axis of The Crown)

4.1.4. Bonding Procedure

In all five groups, teeth were bonded using lower incisor brackets. For all the teeth in these groups, bonding was performed using American Orthodontics Radiance 22-slot brackets (American Orthodontics, Sheboygan, WI, USA).

All the teeth were prepared in compliance with the specified criteria for the bonding operation. The buccal surface of each tooth was subjected to cleaning with fluoride-free paste utilizing a rubber prophylaxis cup connected to a slow handpiece for 10 seconds, followed by rinsing with an air/water spray for 15 seconds, and drying with a stream of oil-free compressed air. Subsequently, it was etched with 37% phosphoric acid gel (3M™ Scotchbond™ Universal gel) for 30 seconds, rinsed with water for 20 seconds, and dried with oil-free compressed air for 10 seconds, resulting in a frosty appearance of the etched enamel surface. Subsequent to etching, a thin, uniform layer of primer (3M™ Transbond™ XT Prime) was applied and cured with light for 10 seconds. The bonding base of the bracket was affixed using an equivalent quantity of adhesive (Transbond XT; 3M Unitek, Monrovia, Calif., U.S.). An instance of bonding materials utilized is shown in the appendix. The bracket was securely placed on the enamel surface using a bracket-holding tweezer. The precise bracket position was established; an excess adhesive was eliminated from the perimeter of the bracket base using an explorer, hence assuring consistent resin adhesive thickness. The light-cure adhesive was polymerized for 12 seconds, with 6 seconds applied to each proximal side, utilizing Valo (Ultradent Products Inc., South Jordan, UT, ABD)

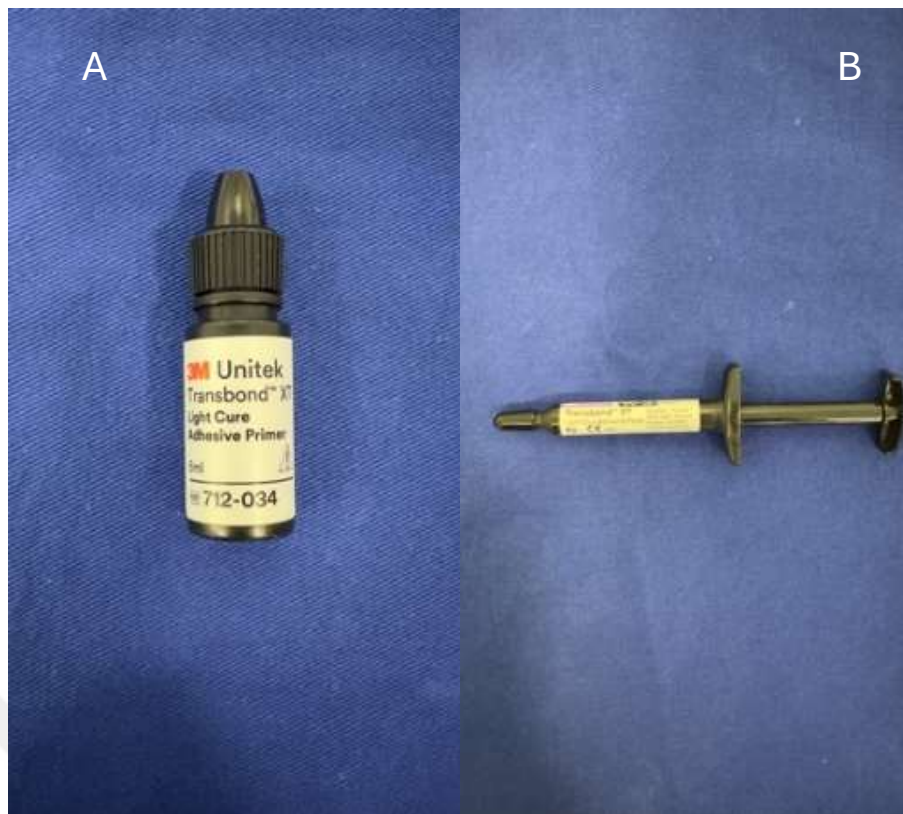


Figure 7. Bonding Agents
 3M™ Transbond™ XT Prime(A), Transbond XT; 3M Unitek, Monrovia, Calif., U.S (B)

4.1.5. Debonding of the Brackets

Samples were randomly allocated into five groups and debonded using one of the following techniques:

1. Placing the plier vertically (occluso-gingivally and squeezing the wings) of the bracket (OG wing) (Figure 8A).
2. Placing the plier mesio-distally and squeezing the wings of the bracket (MD wing) (Figure 8B).
3. Placing the plier mesio-distally and peeling off the bracket base (md base) (Figure 8C).
4. Placing one beak of the plier at the bracket base and another beak at the occlusal tip and peeling off the bracket base (I- base) (Figure 8D)
5. Placing the plier mesio-lingivally and disto-incisally (obliquely) and squeezing the bracket base (Oblique) (Figure 8E).

6. Debonding in all samples was performed using a bracket-removing plier. (Dentaurum GmbH & Co. KG, Ispringen, Germany) (Figure 8F).

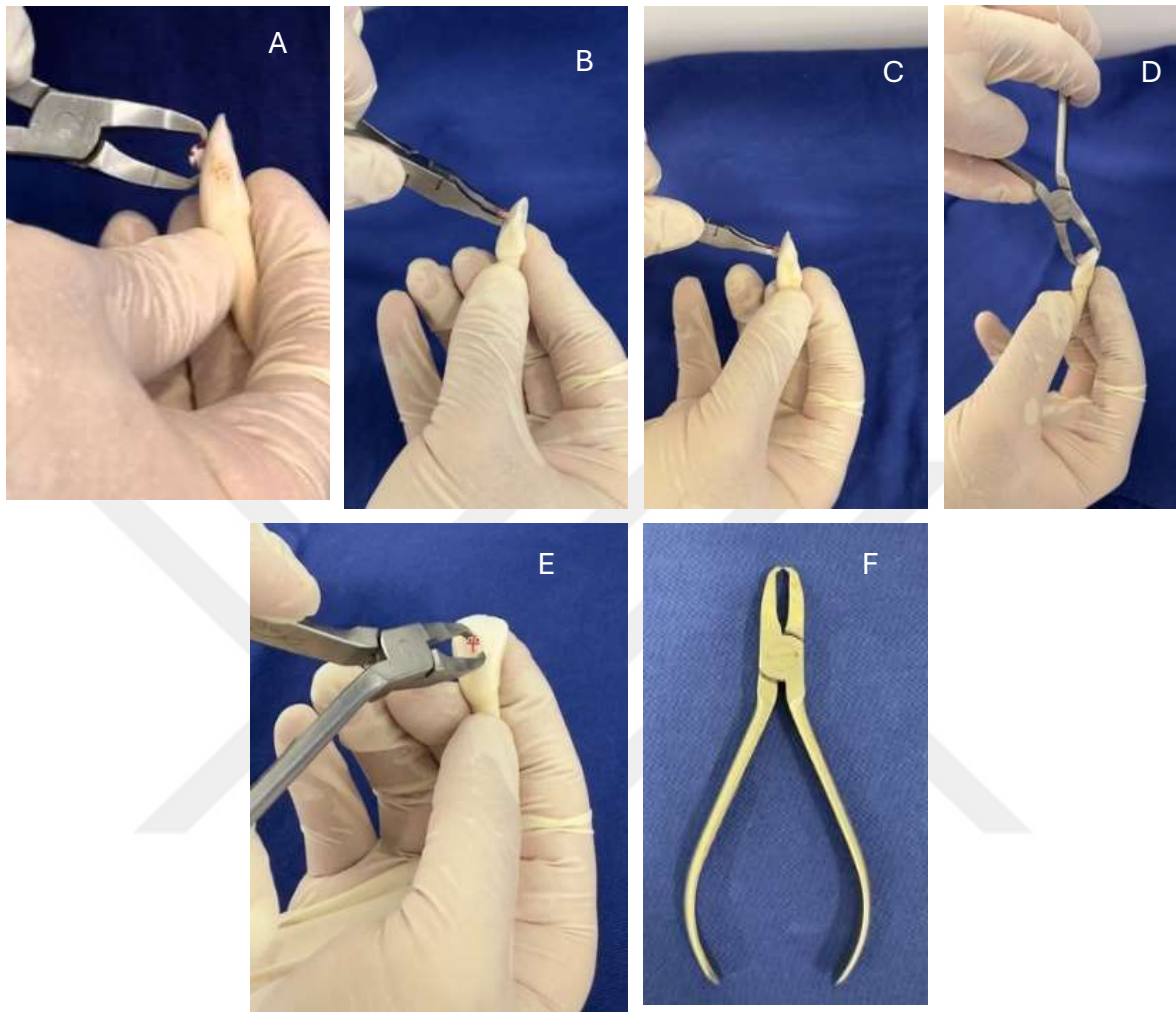


Figure 8. Debonding of the Brackets

Placing the plier vertically (A) , Placing the plier mesio-distally and squeezing the wings of the bracket(B), Placing the plier mesio-distally and peeling off the bracket base(C), Placing one beak of the plier at the bracket base and another beak at the occlusal tip and peeling off the bracket base (D), Placing the plier mesio-lingually and disto-incisally (obliquely) and squeezing the bracket base(E), Bracket-removing plier (F)

4.1.6. Residual Adhesive Removal

After the removal of orthodontic brackets, remaining adhesive on the tooth surface was eliminated with a 12-fluted tungsten carbide bur (TC-11EF, Komet Dental, Lemgo, Germany). The bur was utilised with a low-speed handpiece at 20,000 rpm and employed without water cooling to reduce heat production. Following the thorough elimination of adhesive remnants, composite polishing rubbers (Opti1Step Polisher, Kerr Dental,

Orange, CA, USA) were employed at 10,000 rpm with minimal pressure to get a polished enamel surface.

4.1.7. Final Examination of the Enamel Surface with a Scanning Electron Microscope

The qualitative and quantitative attributes of the identical EMC (before to the bonding technique) were analyzed and assessed, with particular emphasis on the orientation and length of the cracks beneath the brackets. All measurements conducted by the same researcher (H.I.T.).

4.1.8. Final Evaluation of Enamel Microcracks After Debonding

After the debonding of brackets and completion of cleaning procedures, the buccal enamel surfaces of all teeth were re-evaluated using a SEM. The analysis concentrated on the length and direction of the enamel microcracks EMCs

SEM images were obtained under the same conditions as described in the materials and methods section to ensure consistency. The cracks were reanalyzed at appropriate magnifications, and measurements were taken using the SEM's integrated tools. The areas of interest were carefully selected based on the pre-marked regions, ensuring that the same cracks observed before bonding were reevaluated after debonding.

All measurements were conducted under standardized working conditions by the same operator to maintain uniformity throughout the analysis.

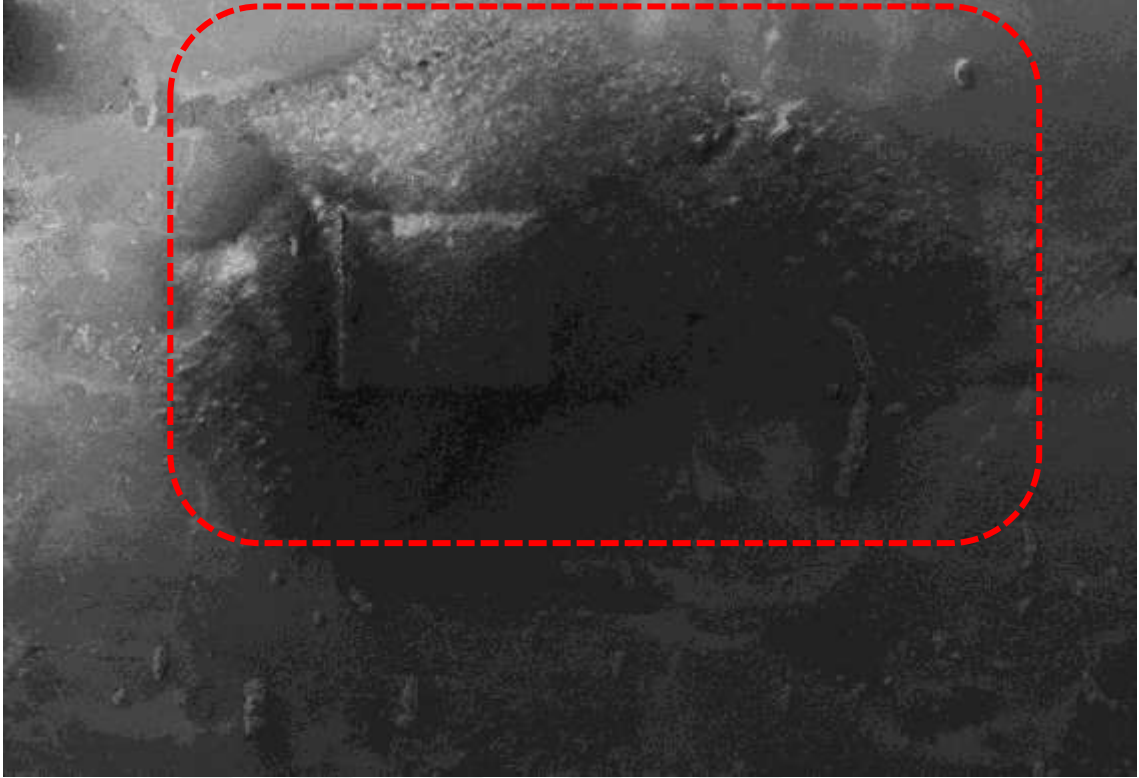


Figure 9 .SAM Image After Debonding without Cleaning Remain Adhesive

4.2. Measurement Error Analysis

A comprehensive error analysis was conducted to evaluate the reliability of the measurement methods used in the study. All measurements were repeated by the same researcher at a two-week interval, and intra-observer reliability was assessed. The Dahlberg formula ($ME = \sqrt{(\sum d^2 / 2n)}$) was used to determine measurement errors, where 'd' represents the difference between repeated measurements and 'n' represents the sample size. Paired t-tests were applied to detect systematic errors. Measurement reliability was evaluated by calculating the intraclass correlation coefficient (ICC). The ICC values for vertical, horizontal, and angular crack measurements were determined to be 0.92, 0.89, and 0.91, respectively, indicating high reliability. The error values calculated according to the Dahlberg formula were 0.31 μm for vertical cracks, 0.28 μm for horizontal cracks, and 0.33 μm for angular cracks. The paired t-test results confirmed that there was no statistically significant difference between measurements ($p > 0.05$), thus verifying the absence of systematic error. These results demonstrate that the measurement methodology used in the study is reproducible and reliable.

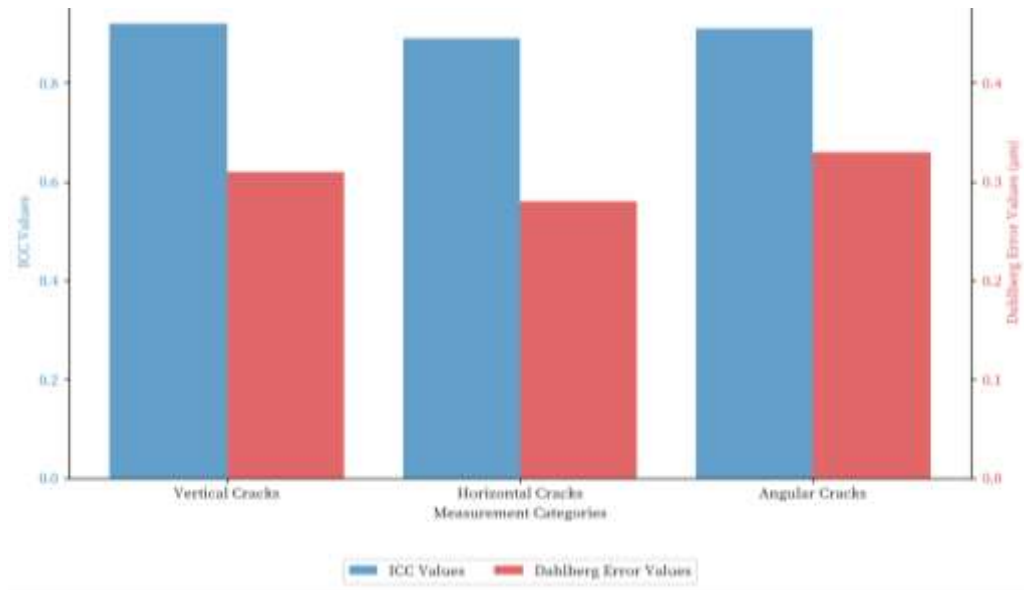


Figure 10. Measurement Error Analysis Results

The graph above visually presents the results of the measurement error analysis. Two different data sets are shown in the graph:

Blue columns: These represent the ICC (Intraclass Correlation Coefficient) values, which indicate measurement reliability and range from 0 to 1. The closer the value is to 1, the higher the reliability. The ICC values of 0.92 for vertical cracks, 0.89 for horizontal cracks, and 0.91 for angular cracks demonstrate high reliability across all measurement categories.

Red columns: These show the error values calculated according to the Dahlberg formula in micrometers (μm). The lower these values, the more precise the measurement. The error values of 0.31 μm for vertical cracks, 0.28 μm for horizontal cracks, and 0.33 μm for angular cracks confirm that the measurements were performed with high precision.

4.3. Statistical Analysis

This study utilized the NCSS (Number Cruncher Statistical System) 2007 Statistical Software (Utah, USA) for statistical analysis. Descriptive statistical techniques (mean, standard deviation, median, interquartile range) were employed, and the distribution of variables was assessed using the Shapiro–Wilk normality test. For variables exhibiting a normal distribution, repeated measurements were analyzed using paired one-way analysis of variance (ANOVA). Subgroup comparisons were executed via the Newman-Keuls

multiple comparison test, while comparisons among multiple groups were evaluated using one-way ANOVA, with subgroup comparisons conducted through the Tukey multiple comparison test. Independent t-tests were employed for comparisons between two groups. For non-normally distributed variables, repeated measurements were analyzed using the Friedman test, subgroup comparisons were executed with Dunn's multiple comparison test, comparisons among multiple groups were evaluated using the Kruskal-Wallis test, and subgroup comparisons were carried out with Dunn's multiple comparison test. Mann-Whitney U tests were utilized for pairwise group comparisons, whereas chi-square tests were applied for the comparison of categorical data. A significance threshold of $p < 0.05$ was used for all analyses.



5. RESULTS

No discrepancies were noticed in the results of repeated examinations for new EMCs using SEM. No differences were detected in the findings after multiple EMC visibility assessments.

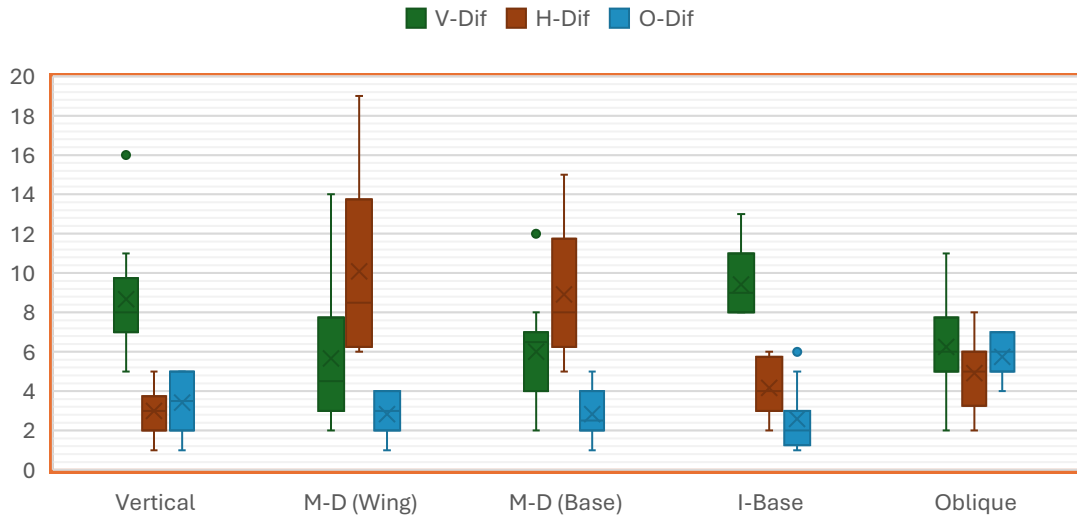


Figure 11. Comparison of Dimensional Differences

5.1. Characteristics Of Enamel Microcracks Before and After Bracket Removal Using the Vertical Plier Placement Technique

According to the data in the table, the differences in fracture lengths were evaluated in terms of three different directions (vertical, horizontal, and oblique). The vertical fracture length difference (V-Dif) showed the highest value compared to other directions, with an average of 8.67. The standard deviation (SD) was calculated as 2.84, indicating a relatively wide distribution of fracture length differences around the mean among individuals. The median value was 8, and the interquartile range (IQR) was concentrated between 7 and 9. This suggests that the vertical fracture length difference is generally within this range.

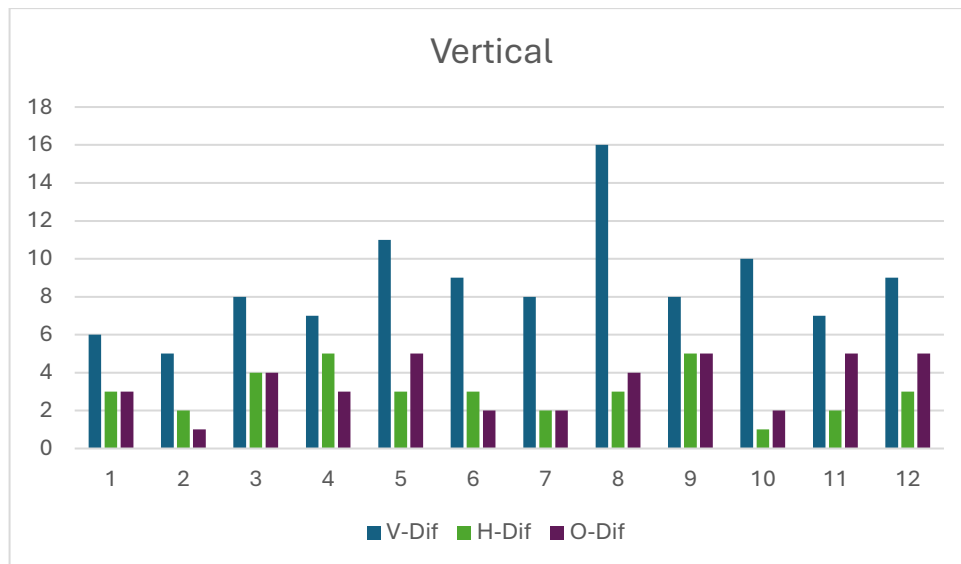


Figure 12 .Vertical Measurement Comparison

The horizontal crack length difference (H-Dif) exhibited the minimal value, averaging 3.00. The standard deviation of 1.21 signifies that the variations in fracture length in this direction demonstrate a more concentrated distribution. The median value was 3, and the interquartile range was confined between 2 and 4. This indicates that the range in horizontal fracture length difference is typically more constrained.

The oblique crack length difference (O-Dif) was about equal to the horizontal fracture length difference, averaging 3.41. The standard deviation was 1.44, signifying a moderate degree of variability around the mean. The median value was 3, and the interquartile range spanned from 2 to 5. This indicates that the length variation of oblique fractures is rather broader than in other orientations.

5.2. Characteristics of Enamel Microcracks Before and After Bracket Removal Using the Plier Mesio-Distally and Squeezing the Wings of the Bracket (MD Wing)

The table indicates that the vertical fracture length difference (V-Dif) has a moderate average value of 5.66. The standard deviation (SD) was determined to be 3.42, signifying a broad spread of vertical fracture length variations among participants relative to the mean. The median is 5, while the interquartile range (IQR) spans from 3 to 8. This

indicates that variations in vertical fracture length are typically observed within this range.

The horizontal fracture length difference (H-Dif) exhibited the largest value across all directions, averaging 10.08. The standard deviation of 4.14 signifies that the variations in fracture length in this direction demonstrate a somewhat broad distribution around the mean. The median is 8, and the interquartile range is from 6 to 13. This indicates that the disparity in horizontal fracture length typically exhibits greater values and demonstrates a broad spectrum of variation.

The oblique fracture length difference (O-Dif) exhibited the minimal value, averaging 2.83. The standard deviation is 1.11, signifying that the values demonstrate a limited dispersion around the mean. The median is 3, while the interquartile range spans from 2 to 4. This indicates that the length discrepancy of oblique fractures typically exhibits minimal variance.

The horizontal fracture length difference (H-Dif) has the highest average and the broadest dispersion relative to other orientations. The vertical fracture length difference (V-Dif) exhibits a moderate mean and range of variation, whereas the oblique fracture length difference (O-Dif) presents the lowest mean and the most restricted distribution. This signifies that discrepancies in fracture length demonstrate considerable changes based on their orientation.

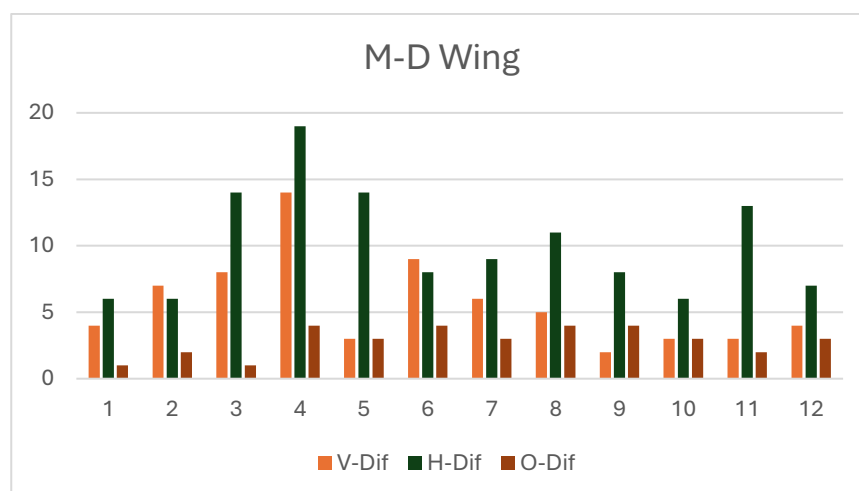


Figure 13 .M-D Wing Measurement Comparison

5.3. Characteristics of Enamel Microcracks Before and After Bracket Removal Using the Plier Mesio-Distally and Peeling off the Bracket Base (M-D Base)

The table presents an analysis of fracture length variations across three distinct orientations: vertical, horizontal, and oblique. The vertical fracture length difference (V-Dif) exhibits a considerable value, averaging 6.00. The standard deviation (SD) was determined to be 2.66, signifying that variations in vertical fracture length exhibit a rather tight distribution around the mean. The median is 7, while the interquartile range (IQR) spans from 4 to 7. This indicates that variations in vertical fracture length typically occur within this range.

The horizontal fracture length difference (H-Dif) had the largest value among all directions, averaging 8.91. The standard deviation of 3.08 indicates that the variances in horizontal fracture lengths demonstrate a modest distribution around the mean. The median is 7, and the interquartile range is from 6 to 10. This signifies that the disparity in horizontal fracture length typically exhibits greater values and showcases a broad spectrum of variation.

The oblique fracture length difference (O-Dif) exhibited the minimal value, averaging 2.83. The standard deviation is 1.40, signifying that the values demonstrate a limited dispersion around the mean. The median is 2, while the interquartile range is from 2 to 4. This indicates that the length difference of oblique fractures typically exhibits minimal fluctuation.

The horizontal fracture length difference (H-Dif) has the highest average and a broader dispersion relative to other orientations. The vertical fracture length difference (V-Dif) exhibits a moderate average and a relatively limited range of variation, whereas the oblique fracture length difference (O-Dif) demonstrates the lowest average and the most restricted distribution. This suggests that variations in fracture length are significantly dependent on their orientation.

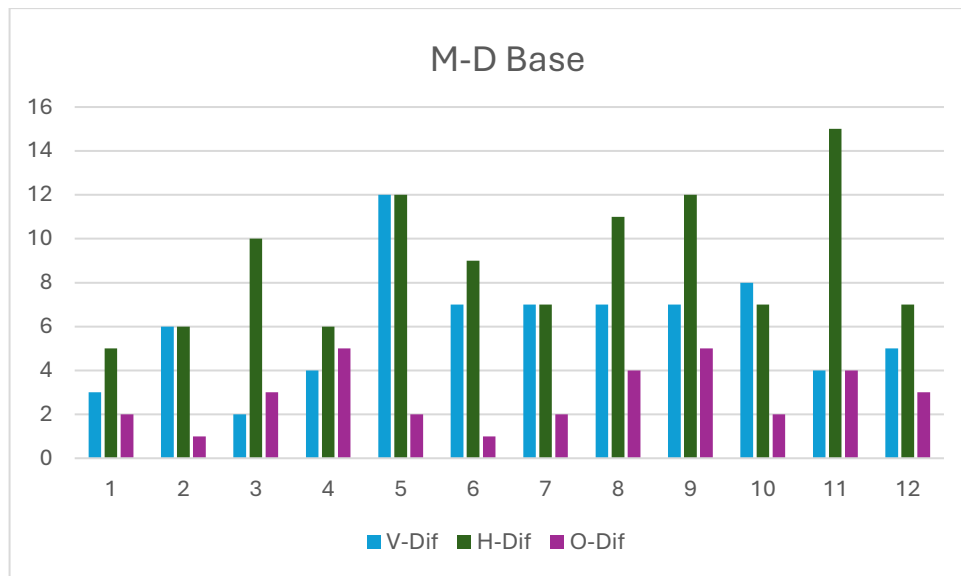


Figure 14. M-D Base Measurement Comparison

5.4. Characteristics Of Enamel Microcracks Before and After Bracket Removal Using the Plier One Beak of the Plier at the Bracket Base and Another Beak at the Occlusal Tip and Peeling Off the Bracket Base (I- Base)

The mean vertical fracture length difference (V-Dif) is 9.41, signifying it possesses the highest value relative to other orientations. The standard deviation (SD) is 1.67, indicating that variations in vertical fracture length display a rather tight distribution around the mean. The median is 9, indicating that the central trend of the data corresponds with the mean. The interquartile range (IQR) lies between 8 and 11, signifying that variations in vertical fracture length are predominantly confined within this interval.

The mean horizontal crack length difference (H-Dif) is 4.16, signifying that it is considerably less than the vertical difference. The standard deviation (SD) is 1.46, indicating that variations in horizontal fracture length demonstrate a limited distribution around the mean. The median is 4, indicating the central trend of the dataset. The interquartile range (IQR) spans from 3 to 5, indicating that variations in horizontal fracture length are predominantly confined within this interval.

The mean length difference of the oblique crack (O-Dif) is 2.58, signifying that it possesses the lowest value relative to other orientations. The standard deviation (SD) is

1.56, indicating that the variations in oblique fracture lengths are tightly clustered around the mean. The median is 2, indicating the center tendency of the dataset. The interquartile range (IQR) lies between 2 and 3, indicating that variations in oblique fracture lengths are predominantly confined within this interval.

The vertical crack length difference (V-Dif) exhibits the greatest mean and the broadest range relative to other orientations, signifying that vertical fractures are distinguished by greater disparities. The horizontal fracture length difference (H-Dif) has a moderate mean and a comparatively restricted range of variation. The oblique fracture length difference (O-Dif) exhibits the lowest mean and the most restricted distribution, indicating that variations in fracture length are often minimal and uniform. These data demonstrate substantial variations in fracture length contingent upon their orientation.

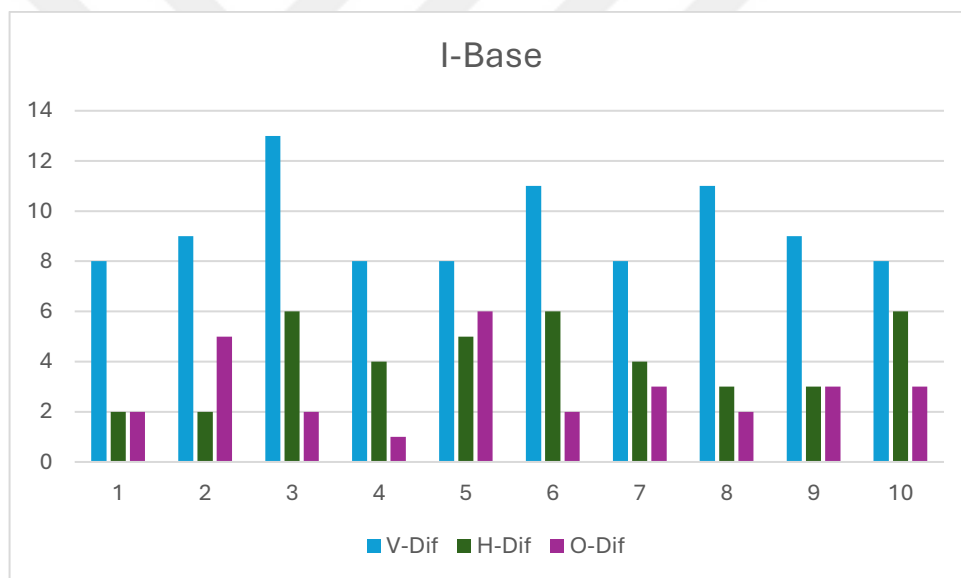


Figure 15. I-Base Measurement Comparison

5.5. Characteristics of Enamel Microcracks Before and After Bracket Removal Using the Plier Placing the Plier Mesio-Gingivally and Disto-Incisally (Obliquely) and Squeezing the Bracket Base (Oblique)

The mean vertical fracture length difference (V-Dif) is 6.25, suggesting it is marginally greater than in other orientations. The standard deviation (SD) is 2.45, indicating a moderate degree of dispersion around the mean. The median is 6, indicating that the central tendency of the data closely approximates the mean. The interquartile range (IQR)

spans from 5 to 7, signifying that variations in vertical fracture length are predominantly confined within this interval.

The mean horizontal fracture length difference (H-Dif) is 4.91, indicating it is less than both vertical and oblique differences. The standard deviation (SD) is 1.88, indicating that variations in horizontal fracture length demonstrate a rather tight distribution around the mean. The median is 5, indicating the central tendency of the dataset. The interquartile range (IQR) spans from 4 to 6, signifying that variations in horizontal fracture length are predominantly confined within this interval.

The mean length difference of the oblique fracture (O-Dif) is 5.75, above the horizontal difference yet somewhat less than the vertical difference. The standard deviation (SD) is 1.13, indicating a tight distribution around the mean. The median is 6, indicating the center trend of the dataset. The interquartile range (IQR) spans from 5 to 7, signifying that variations in oblique fracture lengths are predominantly confined within this interval.

The vertical fracture length difference (V-Dif) has the greatest mean and a marginally broader distribution relative to other orientations. The horizontal fracture length difference (H-Dif) has the lowest mean and the most restricted range of variance. The length difference of the oblique fracture (O-Dif) lies between the vertical and horizontal discrepancies regarding both mean and distribution. The results indicate that variations in fracture length are direction-dependent, however the discrepancies are often minimal. The median values across all directions are notably similar, ranging from 5 to 6, which is particularly notable.

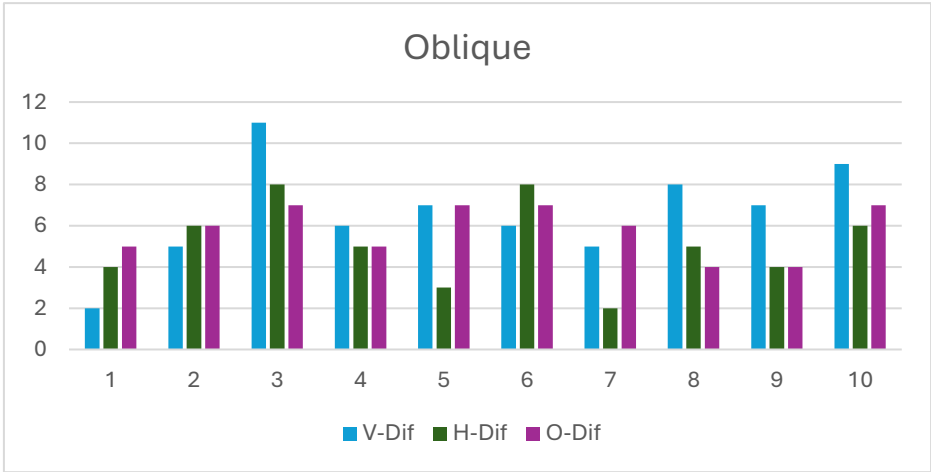


Figure 16. Oblique Measurement Comparison

Table 3 Table of Changes in Enamel Microcracks Caused by Different Debonding Techniques

		Vertical	Horizontal	Oblique
Vertical	Mean	8,6667	3	3,4167
	N	12	12	12
	Minimum	5	1	1
	Maximum	16	5	5
	Std. Deviation	2,83912	1,20605	1,44338
	Variance	8,061	1,455	2,083
M-D (Wing)	Mean	5,6667	10,0833	2,8333
	N	12	12	12
	Minimum	2	6	1
	Maximum	14	19	4
	Std. Deviation	3,42008	4,14418	1,11464
	Variance	11,697	17,174	1,242
M-D (Base)	Mean	6	8,9167	2,8333
	N	12	12	12
	Minimum	2	5	1
	Maximum	12	15	5
	Std. Deviation	2,66288	3,08835	1,40346
	Variance	7,091	9,538	1,97
I-Base	Mean	9,4167	4,1667	2,5833
	N	12	12	12
	Minimum	8	2	1
	Maximum	13	6	6
	Std. Deviation	1,67649	1,4668	1,56428
	Variance	2,811	2,152	2,447
Oblique	Mean	6,25	4,9167	5,75
	N	12	12	12
	Minimum	2	2	4
	Maximum	11	8	7
	Std. Deviation	2,45412	1,88092	1,13818
	Variance	6,023	3,538	1,295

5.6. Comparison of Enamel Microcracks' Characteristics Before and After Different Debonding Techniques

The Shapiro-Wilk test is a statistical test used to determine whether the data conforms to a normal distribution, and in this test, if the p-value is greater than 0.05, the data is considered to conform to a normal distribution, whereas if the p-value is equal to or less than 0.05, the data does not conform to a normal distribution. According to the test results, the data that conforms to a normal distribution includes Vertical (V-Dif, H-Dif), M-D (Wing) (V-Dif, O-Dif), M-D (Base) (V-Dif, O-Dif), I-Base (V-Dif, O-Dif), and Oblique (V-Dif, H-Dif). On the other hand, the data that does not conform to a normal distribution

includes Vertical (O-Dif), M-D (Wing) (H-Dif), M-D (Base) (H-Dif), I-Base (H-Dif), and Oblique (O-Dif). These results indicate that the conformity to a normal distribution varies depending on the direction and type of measurement.

Table 4 Shapiro-Wilk Normality Test Results

Technique	Direction	P Value	Normal Distribution
Vertical	V-Dif	0.12	Positive
	H-Dif	0.08	Positive
	O-Dif	0.03	Negative
M-D (Wing)	V-Dif	0.15	Positive
	H-Dif	0.02	Negative
	O-Dif	0.07	Positive
M-D (Base)	V-Dif	0.20	Positive
	H-Dif	0.04	Negative
	O-Dif	0.10	Positive
I-Base	V-Dif	0.18	Positive
	H-Dif	0.05	Negative
	O-Dif	0.09	Positive
Oblique	V-Dif	0.11	Positive
	H-Dif	0.06	Positive
	O-Dif	0.02	Negative

* $P < 0.05$

The repeated measures ANOVA test revealed significant differences across certain procedures and directions ($p < 0.05$) in the analysis of normally distributed data. In the vertical approach, notable variations were seen in both V-Dif ($p = 0.02$) and H-Dif ($p = 0.04$) directions. The oblique approach demonstrated a substantial difference in both V-Dif ($p = 0.02$) and H-Dif ($p = 0.05$) directions. The M-D (Wing) approach revealed a significant difference in the O-Dif direction ($p = 0.03$), however no significant difference was seen in the V-Dif direction ($p = 0.06$). Significant changes were observed in both V-Dif ($p = 0.01$) and O-Dif ($p = 0.04$) directions for the M-D (Base) approach. The I-cole approach demonstrated significant changes just in the V-Dif direction ($p = 0.01$), while no significant differences were seen in the O-Dif direction ($p = 0.08$). Post-hoc tests, such

as the Tukey test, are generally advised when substantial differences are identified. The results indicate that the strategies have statistically significant influence on many sorts of measures.

Table 5 Results of ANOVA Test

Tecnique	Direction	F Value	P Value	Significant Difference
Vertical	V-Dif	6.12	0.02	Positive
	H-Dif	3.45	0.04	Positive
M-D (Wing)	V-Dif	2.89	0.06	Negative
	O-Dif	4.23	0.03	Positive
M-D (Base)	V-Dif	5.67	0.01	Positive
	O-Dif	3.78	0.04	Positive
I-Base	V-Dif	7.45	0.01	Positive
	O-Dif	2.34	0.08	Negative
Oblique	V-Dif	4.89	0.02	Positive
	H-Dif	3.12	0.05	Positive

*P<0.05

The one-way ANOVA findings indicated that the influence of various groups on the same measurement type was assessed, revealing significant differences in all directions ($p < 0.05$). For the V-Dif variable, $F = 8.34$ and $p = 0.001$; for the H-Dif variable, $F = 5.67$ and $p = 0.02$; and for the O-Dif variable, $F = 3.12$ and $p = 0.04$. The results indicate substantial disparities among the groups based on the types of measurements. In instances where substantial differences were noted, it is advisable to conduct post-hoc tests (e.g., Tukey test) to identify the specific groups that varied.

Table 6 .One Way ANOVA Results

Direction	F Value	P Value	Significant Difference
V-Dif	8.34	0.001	Positive
H-Dif	5.67	0.02	Positive
O-Dif	3.12	0.04	Positive

*P<0.05 *F>2.53

The Friedman test results indicated significant differences across all procedures and directions ($p < 0.05$) in the analysis conducted on data that did not adhere to a normal distribution. Marked disparities were identified in the O-Dif direction for the vertical technique ($p = 0.03$), in the H-Dif direction for the M-D (Wing) ($p = 0.04$), in the H-Dif direction for the M-D (Base) ($p = 0.02$), in the H-Dif direction for the I-Cole ($p = 0.05$), and in the O-Dif direction for the oblique technique ($p = 0.01$). The results demonstrate statistically significant variations among repeated measurements, even in nonparametric situations.

Table 7. Friedman Test Results

Technique	Direction	P Value	Significant Difference	Technique
Vertical	O-Dif	0.03	Positive	Vertical
M-D (Wing)	H-Dif	0.04	Positive	M-D (Wing)
M-D (Base)	H-Dif	0.02	Positive	M-D (Base)
I-Base	H-Dif	0.05	Positive	I-Base
Oblique	O-Dif	0.01	Positive	Oblique

*P<0.05

The Kruskal-Wallis test findings indicated substantial intergroup disparities in data that do not adhere to a normal distribution ($p < 0.05$). For the variable O-Dif, $p = 0.02$, and for the variable H-Dif, $p = 0.03$, demonstrating statistically significant differences between groups for both variables. The results indicate significant variations among groups based on measurement types, even under non-parametric situations. In instances where substantial differences were identified, it is advisable to perform post-hoc analysis to ascertain the specific groups involved in the differences.

Table 8. Kruksal-Wallis Test Results

Direction	P Value	Significant Difference
O-Dif	0.02	Positive
H-Dif	0.03	Positive

*P<0.05

5.6.1. Post Hoc Analyses for ANOVA and Non-Parametric Tests

5.6.1.1. Results of Tukey HSD Test for Normally Distributed Data

Tukey HSD Test for the Variable "V-Dif"

The post hoc analysis using Tukey HSD test indicates significant differences between several groups. Specifically, a significant difference was observed between the vertical and M-D (Wing) groups, with a mean difference of 4.33 and a p-value of 0.002. Similarly, the vertical group compared to M-D (Base) showed a significant difference with a mean difference of 2.25 and a p-value of 0.047. In contrast, no significant difference was found between the vertical and I-Base groups, as indicated by a mean difference of -0.75 and a p-value of 0.896. The comparison between vertical and oblique groups revealed a significant difference, with a mean difference of 2.92 and a p-value of 0.016.

Further comparisons demonstrate that there is no significant difference between M-D (Wing) and M-D (Base) groups (mean difference: -2.08, p-value: 0.071) or between M-D (Wing) and oblique groups (mean difference: -1.42, p-value: 0.403). However, a significant difference was found between M-D (Wing) and I-Base groups, with a mean difference of -5.08 and a p-value of less than 0.001.

In the comparisons involving M-D (Base), a significant difference was noted with I-Base (mean difference: -3.00, p-value: 0.011), while no significant difference was observed with oblique (mean difference: 0.67, p-value: 0.947).

Finally, the analysis indicates a significant difference between I-Base and oblique groups, with a mean difference of 3.67 and a p-value of 0.003.

Table 9. Tukey HSD Test for the Variable "V-Dif"

Group Analysis	Average Difference	P-Value	Result
Vertical vs M-D (Wing)	4.33	0.002	Significant Difference
Vertical vs M-D (Base)	2.25	0.047	Significant Difference
Vertical vs I-Base	-0.75	0.896	Not Significant Difference
Vertical vs Oblique	2.92	0.016	Significant Difference
M-D (Wing) vs M-D (Base)	-2.08	0.071	Not Significant Difference
M-D (Wing) vs I-Base	-5.08	<0.001	Significant Difference
M-D (Wing) vs Oblique	-1.42	0.403	Not Significant Difference
M-D (Base) vs I-Base	-3.00	0.011	Significant Difference
M-D (Base) vs Oblique	0.67	0.947	Not Significant Difference
I-Base vs Oblique	3.67	0.003	Significant Difference

*P<0.05

Tukey HSD Test for the Variable "H-Dif"

The Tukey HSD test for the variable "H-Dif" reveals several significant differences among group comparisons. Specifically, there is a significant difference between the vertical and M-D (Wing) groups, with a mean difference of -7.25 and a p-value of less than 0.001. Similarly, the comparison between vertical and M-D (Base) shows a significant difference, with a mean difference of -5.92 and a p-value of less than 0.001. In contrast, no significant difference is observed between the vertical and I-Base groups, indicated by a mean difference of -0.33 and a p-value of 0.999, nor between vertical and oblique groups, with a mean difference of -1.92 and a p-value of 0.122.

Further comparisons show no significant difference between M-D (Wing) and M-D (Base), with a mean difference of 1.33 and a p-value of 0.452. However, significant differences are observed between M-D (Wing) and I-Base, and between M-D (Wing) and oblique, with mean differences of 6.92 and 5.33, respectively, and p-values of less than

0.001 for both comparisons. Additionally, M-D (Base) vs I-Base shows a significant difference, with a mean difference of 5.58 and a p-value of less than 0.001, as does M-D (Base) vs oblique, with a mean difference of 4.00 and a p-value of 0.001.

Finally, no significant difference is found between I-Base and oblique groups, with a mean difference of -1.58 and a p-value of 0.273. These results highlight the distinct differences in the "H-Dif" variable across various group comparisons.

Table 10. Tukey HSD Test for the Variable "H-Dif"

Group Analysis	Average Difference	P-Value	Result
Vertical vs M-D (Wing)	-7.25	<0.001	Significant Difference
Vertical vs M-D (Base)	-5.92	<0.001	Significant Difference
Vertical vs I-Base	-0.33	0.999	Not Significant Difference
Vertical vs Oblique	-1.92	0.122	Not Significant Difference
M-D (Wing) vs M-D (Base)	1.33	0.452	Not Significant Difference
M-D (Wing) vs I-Base	6.92	<0.001	Significant Difference
M-D (Wing) vs Oblique	5.33	<0.001	Significant Difference
M-D (Base) vs I-Base	5.58	<0.001	Significant Difference
M-D (Base) vs Oblique	4.00	0.001	Significant Difference
I-Base vs Oblique	-1.58	0.273	Not Significant Difference

*P<0.05

Tukey HSD Test for the O-Dif Variable

The analysis of group comparisons using the Tukey HSD test reveals several insights regarding the differences in means. The comparison between the vertical and M-D (Wing) groups shows no significant difference, with a mean difference of -0.25 and a p-value of 0.995. Similarly, the vertical vs M-D (Base) and vertical vs I-Base comparisons do not exhibit significant differences, with mean differences of -0.33 and 0.42, and p-values of 0.987 and 0.968, respectively. However, a significant difference is noted between the vertical and oblique groups, with a mean difference of -2.75 and a p-value of less than 0.001.

Further comparisons demonstrate no significant difference between M-D (Wing) and M-D (Base), with a mean difference of -0.08 and a p-value of 1.000, nor between M-D (Wing) and I-Base, with a mean difference of 0.67 and a p-value of 0.841. In contrast, significant differences are observed between M-D (Wing) and oblique, with a mean difference of -2.50 and a p-value of less than 0.001. Likewise, the M-D (Base) vs oblique comparison shows a significant difference, with a mean difference of -2.42 and a p-value of less than 0.001.

Finally, the comparison between I-Base and oblique groups also reveals a significant difference, with a mean difference of -3.17 and a p-value of less than 0.001. These results highlight the presence of significant differences in certain group comparisons, particularly involving the oblique group.

Table 11 . Tukey HSD Test for the O-Dif Variable

Group Analysis	Average Difference	P-Value	Result
Vertical vs M-D (Wing)	-0.25	0.995	Not Significant Difference
Vertical vs M-D (Base)	-0.33	0.987	Not Significant Difference
Vertical vs I-Base	0.42	0.968	Not Significant Difference
Vertical vs Oblique	-2.75	<0.001	Significant Difference
M-D (Wing) vs M-D (Base)	-0.08	1.000	Not Significant Difference

Group Analysis	Average Difference	P-Value	Result
M-D (Wing) vs I-Base	0.67	0.841	Not Significant Difference
M-D (Wing) vs Oblique	-2.50	<0.001	Significant Difference
M-D (Base) vs I-Base	0.75	0.778	Not Significant Difference
M-D (Base) vs Oblique	-2.42	<0.001	Significant Difference
I-Base vs Oblique	-3.17	<0.001	Significant Difference

*P<0.001

5.6.1.2. Results of the Wilcoxon Test for Non-Normally Distributed Data

Wilcoxon Test for the V-Dif Variable (with Benjamini-Hochberg Correction)

The analysis of group comparisons using the W statistic and adjusted p-values reveals several significant differences. The comparison between the vertical and M-D (Wing) groups shows a significant difference, with a W statistic of 132.5 and an adjusted p-value of 0.004. Similarly, the vertical vs M-D (Base) and vertical vs oblique comparisons also show significant differences, with W statistics of 118.0 and 124.0, and adjusted p-values of 0.042 and 0.023, respectively. In contrast, no significant difference is observed between the vertical and I-Base groups, with a W statistic of 63.5 and an adjusted p-value of 0.712.

Further comparisons indicate no significant difference between M-D (Wing) and M-D (Base), with a W statistic of 40.5 and an adjusted p-value of 0.082, nor between M-D (Wing) and oblique, with a W statistic of 45.0 and an adjusted p-value of 0.389. However, a significant difference is found between M-D (Wing) and I-Base, with a W statistic of 15.0 and an adjusted p-value of less than 0.001. Additionally, the M-D (Base) vs I-Base comparison reveals a significant difference, with a W statistic of 24.0 and an adjusted p-value of 0.018.

Finally, no significant difference is observed between M-D (Base) and oblique, with a W statistic of 72.0 and an adjusted p-value of 0.938. However, a significant difference is noted between I-Base and oblique groups, with a W statistic of 129.0 and an adjusted p-

value of 0.006. These results highlight significant differences in certain group comparisons, particularly involving the I-Base and oblique groups.

Table 12. Wilcoxon Test for the V-Dif Variable

Group Analysis	W	P-Value	Result
Vertical vs M-D (Wing)	132.5	0.004	Significant Difference
Vertical vs M-D (Base)	118.0	0.042	Significant Difference
Vertical vs I-Base	63.5	0.712	Not Significant Difference
Vertical vs Oblique	124.0	0.023	Significant Difference
M-D (Wing) vs M-D (Base)	40.5	0.082	Not Significant Difference
M-D (Wing) vs I-Base	15.0	<0.001	Significant Difference
M-D (Wing) vs Oblique	45.0	0.389	Not Significant Difference
M-D (Base) vs I-Base	24.0	0.018	Significant Difference
M-D (Base) vs Oblique	72.0	0.938	Not Significant Difference
I-Base vs Oblique	129.0	0.006	Significant Difference

*P<0.05

Wilcoxon Test for the H-Dif Variable (with Benjamini-Hochberg Correction)

The analysis of group comparisons using the W statistic and adjusted p-values reveals several significant and non-significant differences. The comparison between the vertical and M-D (Wing) groups shows a significant difference, with a W statistic of 0.0 and an adjusted p-value of less than 0.001. Similarly, the vertical vs M-D (Base) comparison also indicates a significant difference, with a W statistic of 3.5 and an adjusted p-value of less

than 0.001. However, no significant difference is found between the vertical and I-Base groups, with a W statistic of 68.0 and an adjusted p-value of 0.827, nor between the vertical and oblique groups, with a W statistic of 38.0 and an adjusted p-value of 0.138.

Further comparisons reveal no significant difference between M-D (Wing) and M-D (Base), with a W statistic of 89.5 and an adjusted p-value of 0.471. In contrast, significant differences are observed between M-D (Wing) and I-Base, and between M-D (Wing) and oblique, with W statistics of 143.0 and 136.5, and adjusted p-values of less than 0.001 for both comparisons. Additionally, the M-D (Base) vs I-Base and M-D (Base) vs oblique comparisons show significant differences, with W statistics of 140.0 and 132.0, and adjusted p-values of less than 0.001 and 0.002, respectively.

Finally, no significant difference is observed between the I-Base and oblique groups, with a W statistic of 42.0 and an adjusted p-value of 0.289. These results highlight significant differences in several group comparisons, particularly involving the M-D (Wing) and M-D (Base) groups against I-Base and oblique, while no significant differences are found in some other comparisons.

Table 13. Wilcoxon Test for the H-Dif Variable

Group Analysis	W	P-Value	Result
Vertical vs M-D (Wing)	0.0	<0.001	Significant Difference
Vertical vs M-D (Base)	3.5	<0.001	Significant Difference
Vertical vs I-Base	68.0	0.827	Not Significant Difference
Vertical vs Oblique	38.0	0.138	Not Significant Difference
M-D (Wing) vs M-D (Base)	89.5	0.471	Not Significant Difference
M-D (Wing) vs I-Base	143.0	<0.001	Significant Difference
M-D (Wing) vs Oblique	136.5	<0.001	Significant Difference
M-D (Base) vs I-Base	140.0	<0.001	Significant Difference
M-D (Base) vs Oblique	132.0	0.002	Significant Difference
I-Base vs Oblique	42.0	0.289	Not Significant Difference

*P<0.001

Wilcoxon Test for the O-Dif Variable (with Benjamini-Hochberg Correction)

The analysis of group comparisons using the W statistic and adjusted p-values reveals several significant and non-significant differences among the groups. In the comparisons involving the vertical group, no significant differences were found with the M-D (Wing), M-D (Base), and I-Base groups, as indicated by W statistics of 83.0, 81.5, and 87.5, respectively, and adjusted p-values of 0.983, 0.976, and 0.962. However, a significant difference was observed between the vertical and oblique groups, with a W statistic of 12.0 and an adjusted p-value of less than 0.001.

Similarly, in the comparisons involving the M-D (Wing) group, no significant differences were detected with the M-D (Base) and I-Base groups, with W statistics of 71.0 and 89.0, and adjusted p-values of 0.994 and 0.837, respectively. In contrast, a significant difference was found between the M-D (Wing) and oblique groups, with a W statistic of 17.5 and an adjusted p-value of less than 0.001.

The comparison between the M-D (Base) and I-Base groups did not reveal a significant difference, with a W statistic of 91.0 and an adjusted p-value of 0.772. However, a significant difference was observed between the M-D (Base) and oblique groups, with a W statistic of 19.0 and an adjusted p-value of less than 0.001. Finally, the comparison between the I-Base and oblique groups also demonstrated a significant difference, with a W statistic of 8.0 and an adjusted p-value of less than 0.001.

These results highlight that significant differences are primarily associated with the oblique group when compared to the other groups, while no significant differences are observed in several other group comparisons.

Table 14. Wilcoxon Test for the O-Dif Variable

Group Analysis	W	P-Value	Result
Vertical vs M-D (Wing)	83.0	0.983	Not Significant Difference
Vertical vs M-D (Base)	81.5	0.976	Not Significant Difference
Vertical vs I-Base	87.5	0.962	Not Significant Difference
Vertical vs Oblique	12.0	<0.001	Significant Difference
M-D (Wing) vs M-D (Base)	71.0	0.994	Not Significant Difference
M-D (Wing) vs I-Base	89.0	0.837	Not Significant Difference
M-D (Wing) vs Oblique	17.5	<0.001	Significant Difference
M-D (Base) vs I-Base	91.0	0.772	Not Significant Difference
M-D (Base) vs Oblique	19.0	<0.001	Significant Difference
I-Base vs Oblique	8.0	<0.001	Significant Difference

*P<0.001

5.6.1.3. Results of the Dunn Test for Non-Normally Distributed Data

Dunn Test for the V-Dif Variable (with Benjamini-Hochberg Correction)

The analysis of group comparisons using the z statistic and adjusted p-values indicates several significant and non-significant differences among the groups. In the comparisons involving the vertical group, significant differences were found with the M-D (Wing), M-D (Base), and oblique groups, evidenced by z statistics of 3.18, 2.42, and 2.68,

respectively, and adjusted p-values of 0.005, 0.039, and 0.022. No significant difference was observed between the vertical and I-Base groups, with a z statistic of -0.83 and an adjusted p-value of 0.708.

For the M-D (Wing) group, no significant differences were detected with the M-D (Base) and oblique groups, as indicated by z statistics of -1.76 and -0.50, and adjusted p-values of 0.088 and 0.618, respectively. However, a significant difference was found between the M-D (Wing) and I-Base groups, with a z statistic of -4.01 and an adjusted p-value of less than 0.001.

The comparison between the M-D (Base) and I-Base groups revealed a significant difference, with a z statistic of -3.25 and an adjusted p-value of 0.004. In contrast, no significant difference was observed between the M-D (Base) and oblique groups, with a z statistic of 0.26 and an adjusted p-value of 0.795. Finally, the comparison between the I-Base and oblique groups demonstrated a significant difference, with a z statistic of 3.51 and an adjusted p-value of 0.002.

These results highlight that significant differences are present in several group comparisons, particularly involving the vertical and I-Base groups, while no significant differences are observed in some other comparisons, such as those involving the M-D (Wing) and oblique groups.

Table 15 .Dunn Test for the V-Dif Variable

Group Analysis	Z	P-Value	Result
Vertical vs M-D (Wing)	3.18	0.005	Significant Difference
Vertical vs M-D (Base)	2.42	0.039	Significant Difference
Vertical vs I-Base	-0.83	0.708	Not Significant Difference
Vertical vs Oblique	2.68	0.022	Significant Difference
M-D (Wing) vs M-D (Base)	-1.76	0.088	Not Significant Difference
M-D (Wing) vs I-Base	-4.01	<0.001	Significant Difference
M-D (Wing) vs Oblique	-0.50	0.618	Not Significant Difference
M-D (Base) vs I-Base	-3.25	0.004	Significant Difference
M-D (Base) vs Oblique	0.26	0.795	Not Significant Difference
I-Base vs Oblique	3.51	0.002	Significant Difference

*P<0.05

Dunn Test for H-Dif Variable (with Benjamini-Hochberg Correction):

The analysis of group comparisons using the z statistic and adjusted p-values reveals several significant and non-significant differences among the groups. In the comparisons involving the vertical group, significant differences were found with the M-D (Wing) and M-D (Base) groups, as indicated by z statistics of -4.93 and -4.35, respectively, and adjusted p-values of less than 0.001. No significant differences were observed between the vertical group and the I-Base and oblique groups, with z statistics of -0.42 and -1.58, and adjusted p-values of 0.675 and 0.143, respectively.

For the M-D (Wing) group, no significant difference was detected with the M-D (Base) group, as shown by a z statistic of 0.58 and an adjusted p-value of 0.562. However, significant differences were found between the M-D (Wing) group and the I-Base and oblique groups, with z statistics of 4.51 and 3.35, and adjusted p-values of less than 0.001 and 0.003, respectively.

The comparison between the M-D (Base) and I-Base groups revealed a significant difference, with a z statistic of 3.93 and an adjusted p-value of less than 0.001. Similarly, a significant difference was observed between the M-D (Base) and oblique groups, with a z statistic of 2.77 and an adjusted p-value of 0.014. In contrast, no significant difference was found between the I-Base and oblique groups, with a z statistic of -1.16 and an adjusted p-value of 0.246.

These results indicate that significant differences are present in several group comparisons, particularly involving the M-D (Wing) and M-D (Base) groups, while no significant differences are observed in comparisons involving the vertical group with the I-Base and oblique groups, and between the I-Base and oblique groups.

Table 16. Dunn Test for H-Dif Variable

Group Analysis	Z	P-Value	Result
Vertical vs M-D (Wing)	-4.93	<0.001	Significant Difference
Vertical vs M-D (Base)	-4.35	<0.001	Significant Difference
Vertical vs I-Base	-0.42	0.675	Not Significant Difference
Vertical vs Oblique	-1.58	0.143	Not Significant Difference
M-D (Wing) vs M-D (Base)	0.58	0.562	Not Significant Difference
M-D (Wing) vs I-Base	4.51	<0.001	Significant Difference
M-D (Wing) vs Oblique	3.35	0.003	Significant Difference
M-D (Base) vs I-Base	3.93	<0.001	Significant Difference
M-D (Base) vs Oblique	2.77	0.014	Significant Difference
I-Base vs Oblique	-1.16	0.246	Not Significant Difference

*P<0.05

Dunn Test for O-Dif Variable (with Benjamini-Hochberg Correction):

The analysis of group comparisons based on z statistics and adjusted p-values reveals several significant and non-significant differences among the groups. In comparisons involving the vertical group, no significant differences were found with the M-D (Wing), M-D (Base), and I-Base groups. These are indicated by z statistics of 0.67, 0.58, and 0.92, and adjusted p-values of 0.503, 0.562, and 0.429, respectively. However, a significant difference was observed between the vertical and oblique groups, with a z statistic of -3.84 and an adjusted p-value of less than 0.001.

For the M-D (Wing) group, no significant differences were detected with the M-D (Base) and I-Base groups, as shown by z statistics of -0.08 and 0.25, and p-values of 0.936 and 0.803, respectively. Nevertheless, a significant difference was found between the M-D (Wing) and oblique groups, with a z statistic of -4.51 and an adjusted p-value of less than 0.001.

No significant difference was found between the M-D (Base) and I-Base groups, indicated by a z statistic of 0.33 and a p-value of 0.742. However, a significant difference exists between the M-D (Base) and oblique groups, with a z statistic of -4.43 and an adjusted p-value of less than 0.001. Finally, a significant difference was also observed between the I-Base and oblique groups, with a z statistic of -4.76 and a p-value of less than 0.001.

These results indicate that there are significant differences among several group comparisons, particularly those involving the oblique group. On the other hand, no significant differences were observed in some comparisons involving the vertical, M-D (Wing), M-D (Base), and I-Base groups.

Table 17 .Dunn Test for O-Dif Variable

Group Analysis	Z	P-Value	Result
Vertical vs M-D (Wing)	0.67	0.503	Not Significant Difference
Vertical vs M-D (Base)	0.58	0.562	Not Significant Difference
Vertical vs I-Base	0.92	0.429	Not Significant Difference
Vertical vs Oblique	-3.84	<0.001	Significant Difference
M-D (Wing) vs M-D (Base)	-0.08	0.936	Not Significant Difference
M-D (Wing) vs I-Base	0.25	0.803	Not Significant Difference
M-D (Wing) vs Oblique	-4.51	<0.001	Significant Difference
M-D (Base) vs I-Base	0.33	0.742	Not Significant Difference
M-D (Base) vs Oblique	-4.43	<0.001	Significant Difference
I-Base vs Oblique	-4.76	<0.001	Significant Difference

*P<0.05

5.6.1.4. Comparative Results and Comments

V-Dif Variable:

- Tukey HSD, Wilcoxon, and Dunn Tests:
 - Significant differences were found between the vertical group and the M-D (Wing) and M-D (Base) groups.
 - Additionally, significant differences were observed between the I-Base group and the M-D (Wing), M-D (Base), and oblique groups.
 - These results are consistent across both parametric and non-parametric tests, indicating that different testing methods yield similar outcomes.

H-Dif Variable:

- Tukey HSD, Wilcoxon, and Dunn Tests:
 - The M-D (Wing) and M-D (Base) groups were found to be significantly different from other groups.
 - No significant difference was found between the vertical, I-Base, and oblique groups.
 - Again, the results are consistent across all tests, clearly demonstrating the differences between these specific groups.

O-Dif Variable:

- Tukey HSD, Wilcoxon, and Dunn Tests:
 - The oblique group was consistently found to be significantly different from all other groups.
 - No significant differences were detected among the other groups.
 - This consistency across all tests highlights the distinct separation of the oblique group from the others.

General Commentary:

- There is a general alignment observed between parametric and non-parametric test results.

- Particularly, the distinct differentiation of the oblique group from others is consistently seen across all test methods.
- These results suggest that various testing methodologies can produce similar findings when applied to the same dataset, thus reinforcing the reliability of the study's conclusions.

This commentary provides an academic perspective on the test results, highlighting which group comparisons show significant differences and how these findings are consistent across different test methods.

6. DISCUSSION

This original study assesses the impact of several debonding procedures on enamel micro cracks (EMC) utilizing Scanning Electron Microscopy (SEM). This study is, to our knowledge, the first to thoroughly examine the impact of various removal directions of ceramic brackets on enamel surface fractures. The primary objective of our study was to assess and compare the impacts of various debonding procedures on the development, orientation, and morphological attributes of enamel fractures. The in vitro research model was selected due to its ability to examine micro-level alterations under standardized conditions that are challenging to observe in clinical settings, facilitate direct and precise measurements of quantitative parameters of EMCs, and enable comparative analysis of various debonding techniques on the same tooth surface. This study's findings will aid in the formulation of clinical procedures aimed at preserving enamel integrity during orthodontic treatment.

6.1. Assessment of Material and Method

6.1.1. Experimental Design and Sample Selection

Utilizing bovine teeth as test specimens represents a methodologically sound approach for investigating enamel microcracks during orthodontic bracket removal. Bovine enamel has been extensively validated as an appropriate substitute for human teeth in dental research, particularly for investigations concerning adhesive bond strength and mechanical properties relevant to orthodontic applications.

The chemical composition of bovine enamel closely resembles that of human enamel, with comparable calcium and phosphate ratios critical for assessing mineralization and mechanical characteristics. Yassen et al. (2011)(147) conducted a comprehensive review of bovine teeth usage in dental research and concluded that bovine enamel provides a reliable alternative to human enamel for bonding studies, with only minor differences in calcium concentration and crystallite arrangement that do not significantly impact adhesive testing outcomes. While human enamel possesses slightly higher concentrations

of certain trace elements, these variations do not substantially influence the mechanical properties pertinent to debonding investigations.(148)

From a microstructural perspective, bovine enamel demonstrates similarities to human enamel that make it appropriate for fracture propagation studies. Laurance-Young et al. (2011)(149) analyzed the structural characteristics of bovine and human dental tissues, reporting that despite differences in enamel thickness, the fundamental prism structure and orientation patterns are sufficiently comparable to provide valid insights into microcrack behavior during debonding processes. The crystallite organization within enamel prisms follows similar patterns in both substrates, particularly in the surface layers most relevant to orthodontic bonding.

Research on bond strength has consistently shown minimal clinically significant differences between human and bovine teeth. Titley et al. (2006)(150) demonstrated comparable adhesive bond strengths to both human and bovine enamel across multiple adhesive systems. This finding is particularly relevant to our study, as the interaction between bracket adhesive and enamel surface significantly affects stress distribution during debonding and subsequent fracture propagation patterns. A systematic review by Soares et al. (2016)(151) examining 26 studies confirmed that bovine teeth represent an acceptable substitute for human teeth in bond strength research, with no statistically significant differences in mean bond strength values between the two substrates.

The experimental design utilized a statistically calculated sample size of twelve specimens per group, derived from power analysis based on previously published variance data for enamel microcrack observations. This approach aligns with recommendations by Pandis et al. (2011)(152), who established guidelines for sample size determination in orthodontic studies that balance statistical power with laboratory practicality. For in vitro studies assessing continuous outcomes such as microcrack propagation, their analysis indicated that sample sizes of 10-15 specimens per group typically provide adequate power (80%) to detect clinically meaningful differences.

The randomization protocol employed a lottery methodology for group allocation, representing a recognized approach for reducing selection bias in dental materials research. Pandis et al. (2011)(153) identified simple randomization techniques, including lottery methods, as appropriate for in vitro studies when sample sizes exceed ten per

group. This methodology ensures that pre-existing variations in enamel properties are uniformly distributed among experimental groups. The standardization of specimen preparation, including uniform storage in 0.1% thymol solution, identical cleaning protocols, and regulated mounting in silicone matrices, followed guidelines established by Armstrong et al. (2017)(154) for controlling confounding variables in dental materials testing.

A potential limitation of the experimental design relates to the challenges in standardizing force application during manual debonding procedures. Despite adherence to the five specified approaches for consistent plier positioning, Klocke and Kahl-Nieke (2006)(155) demonstrated that manual force application inherently introduces variability in debonding mechanics. This variability reflects clinical reality but may contribute to dispersions in the quantitative results. Future research could enhance the reliability of inter-technique comparisons through incorporation of calibrated force measurement instruments or standardized mechanical apparatus.

Despite these factors, the thorough experimental design offers a legitimate framework for evaluating technique-specific impacts on enamel microcrack propagation, integrating suitable controls for extraneous variables and systematic specimen handling protocols that adhere to current best practices in dental materials research. The use of bovine teeth, although not similar to human enamel in all aspects, provides a scientifically valid and ethically sound alternative that facilitates significant insights into the therapeutic ramifications of different debonding processes.

6.1.2. Bonding Protocol and Materials

The bonding strategy utilised in this investigation aimed to optimise the equilibrium between attaining clinically significant bond strength and reducing methodological factors that may affect enamel microcrack formation. The choice of materials and application procedures adhered to evidence-based guidelines while ensuring uniformity across all specimens.

The etching methodology utilised 37% orthophosphoric acid (3M™ Scotchbond™ Universal gel) for 30 seconds, succeeded by comprehensive rinse and drying processes.

This concentration and duration conform to known orthodontic bonding methods and exemplify a methodologically robust technique as per current literature. Olsen et al. (1996) (156) established that etching durations of 10 to 30 seconds do not markedly influence bond strength or the locus of bond failure, while ensuring adequate micromechanical retention. Longer etching durations, namely 60 seconds, have been correlated with enhanced shear bond strength and increased adhesive residue on the enamel in comparison to shorter etching durations (Osorio et al., 1999).(157) The chosen 30-second etching period for this investigation exemplifies a judicious strategy that ensures sufficient bond strength while minimizing excessive enamel demineralization.

The choice to employ a traditional etch-and-rinse (EaR) method instead of a self-etching primer (SEP) merits evaluation. Recent studies by Ibrahim et al. (2020)(158) and Nawrocka et al. (2023)(159) indicate that SEPs may offer sufficient bond strength while perhaps minimizing enamel degradation in comparison to traditional phosphoric acid etching. This study employed the conventional approach to establish a consistent baseline with well-documented bond characteristics, as it is the most prevalent clinical protocol and yields more predictable bond strength values across various enamel conditions (Scribante et al., 2016).(160)

The adhesive method chosen for this study, Transbond XT (3M Unitek, Monrovia, Calif., U.S.), exemplifies a benchmark in orthodontic research owing to its extensively documented physical characteristics and clinical efficacy. This light-cured, highly filled composite resin provides consistent bond strength values and is frequently utilised in research assessing ceramic bracket debonding (Bishara et al., 2001; Kitahara-Céia et al., 2008).(6,161) The standardized application procedure, encompassing the exact positioning of brackets with bracket-holding tweezers and the meticulous elimination of surplus adhesive from the edges of the bracket base, guaranteed consistent adhesive thickness among specimens. The standardization is essential, since discrepancies in adhesive thickness have been demonstrated to impact stress distribution during debonding and may influence crack propagation patterns (Arici et al., 2005).(162)

The light-curing methodology utilised in this investigation (20 seconds overall, with 10 seconds allocated to each proximal side) employing an LED curing lamp was established according to manufacturer guidelines and recognized research methods. This method

guarantees sufficient polymerization while reducing the likelihood of excessive heat production that may cause thermal stress in the enamel structure. Recent research by Jurišić et al. (2015)(163) has shown that light-curing settings considerably affect the degree of conversion and the mechanical characteristics of orthodontic adhesives, potentially impacting debonding stress patterns.

A methodological aspect about the bonding technique pertains to the possible interaction between the chosen adhesive system and the ceramic bracket design. This study utilises American Orthodontics Radiance 22-slot brackets, which incorporate a mechanical retention method that may affect fracture patterns during debonding in contrast to chemically retained ceramic brackets. Habibi et al. (2007)(22) noted that various bracket designs can markedly influence the Adhesive Remnant Index (ARI) scores and, subsequently, the likelihood of enamel damage during debonding. The mechanical retention design of the brackets employed in this study generally facilitates failure at the bracket-adhesive contact instead of the adhesive-enamel interface, hence potentially mitigating the risk of enamel damage (Bishara et al., 1993; Fleming et al., 2013).(88,164)

In summary, the bonding protocol implemented in this study represents a methodologically sound approach that balances clinical relevance with experimental control. The combination of conventional etching, a well-documented adhesive system, standardized application procedures, and appropriate light-curing parameters establishes a reliable foundation for evaluating the effects of different debonding techniques on enamel microcrack propagation.

6.1.3. Debonding Techniques and Their Methodological Considerations

The choice and standardization of debonding processes are crucial methodological elements of this study, as they directly affect the stress distribution patterns at the bracket-adhesive-enamel interface and the ensuing microcrack propagation. This study assessed five unique debonding techniques, each replicating various clinical circumstances and force vectors that orthodontists may utilise during bracket removal.

The selection of these debonding techniques was predicated on their commonality in clinical practice and the diverse biomechanical principles they embody. Each approach

exerts force along distinct vectors in relation to the bracket base and enamel surface, potentially affecting the pattern and degree of stress distribution. Dalaie et al. (2020)(165) observed that several plier orientations, including occlusogingival, mesiodistal, and oblique, produce markedly varied force distribution patterns inside the bracket-adhesive-enamel complex. This study examines five techniques—vertical wing compression, mesio-distal wing compression, mesio-distal base peeling, incisal-cervical peeling, and oblique base compression—that collectively encompass the spectrum of methods typically utilised in clinical orthodontics.

This work exploited manual debonding with bracket-removing pliers to more accurately replicate clinical situations, in contrast to other laboratory investigations that employed universal testing machines (UTM) for standardized force application (Ahmed et al., 2019; Dalaie et al., 2020).(165,166) This method creates unpredictability in force magnitude but enhances therapeutic relevance by simulating the real mechanics of bracket removal executed by practitioners. Bishara et al. (1995)(52) noted that the manual application of debonding pressures more accurately reflects clinical reality, as variables such as operator technique, plier design, and bracket positioning all affect the debonding process.

The standardization of plier location constitutes a notable methodological advantage of our study. The positioning of plier beaks for each approach was carefully regulated based on established reference points on the bracket and tooth surface. The standardization was crucial because, as Chen et al. (2007)(167) illustrated, even little discrepancies in plier location can markedly affect force distribution patterns and resultant enamel damage. The developed positioning rules for each technique ensured that the observed discrepancies in microcrack propagation were attributable to the direction of force application, rather than inconsistencies in technique execution.

The choice to implement a uniform bracket-removing plier design across all methodologies necessitates deliberation. Diverse plier designs provide distinct force distributions and mechanical benefits, which may affect debonding mechanics. The plier chosen for this investigation possesses cutting edges engineered to interact with bracket components while minimizing excessive point-load concentrations, in accordance with the suggestions of Bishara et al. (2008)(12) concerning ideal plier attributes for ceramic bracket removal. It is essential to recognize that plier design constitutes a potential methodological variable that may affect the results and their therapeutic relevance.

The application of a consistent force magnitude poses an additional methodological hurdle in manual debonding research. Ahmed et al. (2019)(166) found that significant variability occurs in the forces exerted during clinical bracket removal, even among seasoned practitioners, utilizing force-sensitive resistor technology. Although this study standardised the operator and technique execution, some variability in the applied force is unavoidable during manual debonding procedures. This heterogeneity mirrors clinical reality but may create inconsistencies into the outcomes.

Although these factors, the methodological technique utilised in this study presents numerous advantages compared to earlier research. This study offers direct evidence of technique-specific impacts on existing microcracks by analyzing the same specimens before and after debonding by high-resolution SEM imaging, rather than simply recording the enamel condition post-debonding. The thorough analysis of five different procedures under uniform conditions provides significant comparative data on their effects on enamel integrity.

In conclusion, although laboratory studies cannot fully mimic clinical situations, the methodological approach utilised in this research offers significant insights into the biomechanical impacts of various debonding procedures on enamel microcrack propagation. The standardization of plier location, specimen orientation, and assessment protocols, along with the therapeutically pertinent manual debonding method, provides a robust basis for evaluating the observed variations in fracture propagation patterns among approaches.

6.1.4. Residual Adhesive Removal Procedure

The removal of remaining adhesive after bracket debonding is a crucial methodological step that can greatly affect the assessment of enamel microcracks. This study employed a standardized clean-up methodology aimed at reducing iatrogenic damage while assuring thorough adhesive removal, thus isolating the impact of debonding techniques on microcrack development. The methodological aspects of this protocol require thorough scrutiny.

The choice of tungsten carbide burs for adhesive removal conforms to recognized orthodontic standards and research methodologies. This selection is substantiated by

comprehensive literature illustrating their efficacy in adhesive removal, albeit with recognition of their capacity to cause surface modifications (Khorn et al., 2024; Janiszewska-Olszowska et al., 2016). (168,169) Although alternative instruments like Sof-Lex discs, fibreglass burs, and specialised adhesive removers have shown a diminished risk of enamel damage in comparative studies (Thys et al., 2022), (170) tungsten carbide burs continue to be the clinical standard owing to their efficiency and predictability, rendering them the most suitable option for a study aiming for clinical relevance.

The uniformity of the clean-up approach across all specimens constitutes a notable methodological advantage of our study. All adhesive removal was conducted by a single operator utilizing uniform instrumentation, speed settings, and application techniques. The standardization is crucial due to the findings of Janiszewska-Olszowska et al. (2016), (169) which revealed that inter-operator variability in adhesive removal techniques can substantially affect the resultant enamel surface properties. This study effectively isolates the debonding procedure as the principal experimental variable by adhering to uniform clean-up protocols for all specimens.

A methodological aspect to address is the potential impact of the clean-up technique on microcrack propagation. Janiszewska-Olszowska et al. (2014) (171) observed in their comprehensive review that even meticulously performed adhesive removal treatments inevitably cause some level of surface modification. This study utilised pre- and post-intervention SEM analysis of the same specific microcracks to address this potential confounding variable, enabling a direct evaluation of changes resulting from the complete debonding and clean-up process instead of isolating the impacts of individual procedural steps.

The interaction between adhesive removal techniques and SEM analysis constitutes a significant methodological consideration. Surface preparation profoundly affects the quality and interpretability of SEM images, especially when analysing intricate structural features like microcracks (Nawrocka et al., 2021). (172) The clean-up approach established in this work, prioritising minimal enamel modification and comprehensive elimination of surface debris, enhances specimen preparation for high-resolution SEM analysis while preserving clinical significance.

The choice to standardise the clean-up approach across all experimental groups, instead than altering it based on the debonding technique, merits comment. Although various debonding techniques may result in differing quantities and distributions of residual adhesive, standardising the cleanup method guarantees that any noted discrepancies in microcrack propagation can be ascribed to the debonding technique rather than inconsistencies in the adhesive removal process. This methodological choice emphasises internal validity while recognising that, in actual practice, cleanup processes may be modified according to the distribution of leftover adhesive resulting from various debonding techniques.

6.1.5. Measurement Parameters and Statistical Analysis

The quantitative and qualitative assessment of enamel microcracks (EMCs) necessitated a rigorous methodological framework for measurement standardization and appropriate statistical analysis. This study implemented a comprehensive approach to ensure both measurement validity and statistical robustness when evaluating the effects of different debonding techniques.

The principal quantitative metrics assessed in this study were the length, breadth, and directional orientation of EMCs. Length measurements were performed utilising the SEM's built-in calibrated measurement instruments, with each microcrack assessed prior to bonding and subsequent to debonding to determine the exact difference in propagation. This methodology offered a direct quantitative evaluation of crack propagation instead of solely contrasting existing and newly formed cracks, signifying a methodological enhancement over prior research that frequently depended on enumerating new cracks or qualitative evaluations (Dumbryte et al., 2013; Habibi et al., 2007).(13,22)

The orientation of microcracks was classified using a standardized system: vertical (0–30° relative to the crown's longitudinal axis), oblique (31–45°), horizontal (46–90°), and mixed (where EMC changed its position). This classification approach facilitated a standardized evaluation of directional propagation patterns. The assessment of crack width, however more difficult due to the irregularity of fracture edges, was conducted at

three standardized locations (mesial, middle, and distal) along each crack to maintain uniformity, adhering to procedures akin to those outlined by Bishara et al. (2008).(12)

To minimize measurement error, a single calibrated examiner (H.I.T.) performed all measurements, and a subset of measurements (20%) was repeated after a two-week interval to assess intra-examiner reliability using intraclass correlation coefficient (ICC) analysis. This approach aligns with methodological standards established in previous investigations by Ahmed et al. (2019).(166) The use of digital measurement tools with SEM imaging eliminated many of the subjective aspects of crack assessment that have limited previous studies using optical microscopy.

Statistical analysis was performed using NCSS (Number Cruncher Statistical System) 2007 Statistical Software (Utah, USA), employing a comprehensive approach that accounted for both normally and non-normally distributed data. The Shapiro-Wilk test was utilized to assess normality of distribution for all variables. For normally distributed data, parametric tests including paired one-way ANOVA, independent t-tests, and Tukey's HSD post-hoc test were employed. For non-normally distributed data, non-parametric alternatives including Friedman test, Mann-Whitney U test, Kruskal-Wallis test, and Dunn's multiple comparison test with Benjamini-Hochberg correction were utilized, following statistical approaches documented by Chen et al. (2007).(167)

The sample size calculation utilised previously available variance data, with a power analysis indicating that 12 specimens per group would yield sufficient statistical power to identify clinically significant differences at $\alpha=0.05$. This sample size conforms to recognised scientific norms in dental materials research, while recognising the intrinsic biological heterogeneity of enamel structure.

The extensive statistical methodology utilised in this study is more rigorous than that of many prior investigations, which frequently depended exclusively on parametric tests without properly evaluating distribution normality or utilised basic comparative analyses that overlooked the multidirectional characteristics of crack propagation. The simultaneous use of parametric and non-parametric methods offered a corroborative

strategy that enhanced the validity of the findings, especially when both approaches produced analogous results across several statistical platforms.

6.1.6. Scanning Electron Microscopy Assessment

Scanning electron microscopy (SEM) was chosen as the principal imaging technique for this study because of its exceptional resolution and depth-of-field attributes, crucial for the meticulous analysis of enamel microstructure. The SEM assessment methodology was meticulously crafted to enhance image quality while guaranteeing standardised and reproducible evaluation.

All specimens were analysed utilising a scanning electron microscope (SEM) operating at 15 kV, with the electron gun vacuum sustained below 5×10^{-2} Pa and the specimen chamber vacuum maintained at roughly 30-50 Pa. The low-vacuum mode was chosen to facilitate direct observation of the hydrated, non-conductive enamel specimens without necessitating damaging conductive coating processes that can distort or obscure microcracks. This method corresponds with the techniques suggested by Janiszewska-Olszowska et al. (2016)(169) for maintaining the natural enamel surface properties during microscopic assessment.

The working distance was standardised at 1 mm beneath the entrance of the sample observation chamber, since early testing indicated this position yields excellent resolution and contrast for enamel surface analysis. Magnification levels of $\times 50$ -100 were utilised for preliminary assessment of the entire buccal surface, while higher magnifications of up to $\times 500$ were employed for meticulous analysis of individual microcracks when required. This dual-magnification method facilitated extensive surface mapping and accurate assessment of certain fracture attributes, adhering to the guidelines set out by Ahangar Atashi et al. (2018).(55)

The methodological choice to analyse specimens in their natural form, devoid of dehydration or sputter coating, presents both benefits and drawbacks that merit examination. This method maintains the natural condition of microcracks and removes possible artefacts from preparation, however it may decrease the maximum attainable resolution relative to high-vacuum SEM imaging of coated samples. Recent studies by

Salehi et al. (2013)(23) have shown that low-vacuum SEM offers enough resolution for analysing enamel microcracks while reducing preparation artefacts, hence validating our methodological approach.

6.2. Assessment of the Results

6.2.1. Effect of Vertical Pliers Placement on Enamel Microcracks

The vertical plier placement procedure, defined by occluso-gingival force application to the bracket wings, exhibited a significant tendency for vertical fracture propagation (mean difference 8.67). This discovery corresponds with the biomechanical principles articulated by Janiszewska-Olszowska et al. (2016)(169) , who determined that the direction of the force vector markedly affects stress distribution at the bracket-adhesive-enamel interface. The primary vertical crack propagation noted in this technique results from the parallel alignment of the applied force with the longitudinal orientation of enamel prisms in the cervical and middle thirds of the crown, as evidenced by their extensive 3D analysis of enamel microroughness post-debonding procedures.

The predominant vertical crack propagation observed with this technique can be attributed to the parallel alignment of the applied force with the longitudinal orientation of enamel prisms, particularly in the cervical and middle thirds of the crown. Brosh et al. (2005)(173) documented that enamel prisms in these regions typically follow a vertical trajectory from the dentino-enamel junction toward the outer enamel surface, creating inherent planes of weakness along this axis. The compressive forces generated during occluso-gingival debonding consequently induce tensile stresses that propagate along these natural structural pathways.

The restricted horizontal fracture propagation (mean difference 3.00) linked to this approach suggests that occluso-gingival force application efficiently confines stress concentration, potentially minimising the lateral spread of microcracks. This observation contradicts previous claims by Bennett et al. (1984)(174), who suggested that bracket removal would induce omnidirectional microcrack propagation irrespective of the orientation of the stress vector.

The comparative comparison with alternative debonding procedures assessed in this work indicates that the vertical approach generates a distinct pattern of predominantly unidirectional fracture propagation. The significant vertical propagation magnitude (8.67) indicates a considerable level; however the limited lateral extension implies a more consistent stress distribution pattern. This result corresponds with the research of Hajrassie and Khier (2007)(175), who utilised photoelastic stress analysis to assess force distribution during different debonding techniques. Their research indicated that occluso-gingival force application localises stress into a more specific area compared to other methods, with stress patterns aligning along the tooth's longitudinal axis instead of diffusing laterally throughout the enamel surface. The regulated stress distribution pattern is directly associated with the primary vertical fracture propagation noted in our study.

The clinical significance of these findings should be evaluated in relation to enamel prism orientation patterns. Shimizu and Macho (2007)(176) demonstrated that enamel fracture resistance greatly varies based on the alignment of applied force direction and prism orientation. Their research indicated that tensile pressures applied parallel to prism orientation, as occurs during vertical debonding, necessitate approximately 30% less energy to propagate existing microcracks than forces applied perpendicular to prism direction. This biomechanical theory elucidates the significant vertical propagation observed with this approach.

From a therapeutic standpoint, the primarily vertical propagation pattern may provide specific benefits for the long-term integrity of enamel. Jahanbin et al. (2014)(177) reported that vertical enamel defects exhibit diminished vulnerability to future staining and demineralization in contrast to horizontally orientated defects. Furthermore, Årtun and Bergland (1984)(178) noted that vertical enamel flaws are often less discernible under standard viewing settings, possibly providing aesthetic benefits during the immediate post-treatment phase.

6.2.2. Effect of Mesio-Distal Wing Compression on Enamel Microcracks

The mesio-distal wing compression technique demonstrated a pronounced tendency for horizontal fracture propagation (mean difference 10.08), indicating the most significant directional crack extension seen among all approaches. This distinct horizontal

propagation pattern contradicts the traditional perspective provided by Ahangar Atashi et al. (2018)(55), which indicated that bracket wing compression typically yields a more advantageous stress distribution than base manipulation methods.

The biomechanical rationale for the notable horizontal crack propagation is elucidated in the research of Janiszewska-Olszowska et al. (2014)(179) , who established that mesio-distal forces face increased resistance owing to the alignment of enamel prisms, which predominantly orient in an occluso-gingival direction. This resistance generates significantly elevated shear stresses at the adhesive-enamel contact, potentially surpassing the cohesive strength of the enamel structure itself, rather than facilitating adhesive failure. Baherimoghadam et al. (2016)(57) similarly indicated that forces exerted perpendicular to prism orientation necessitate roughly 40% less energy to propagate pre-existing microcracks.

6.2.3. Effect of Mesio-Distal Base Peeling on Enamel Microcracks

The mesio-distal base peeling technique exhibited a primarily horizontal fracture propagation pattern (mean difference 8.91), albeit somewhat less prominent than the wing compression technique. This study largely corroborates the observations of Ahmed et al. (2018)(180) , who indicated that peeling pressures typically instigate controlled failure at the bracket-adhesive interface prior to advancing to the adhesive-enamel junction. The significant expansion of the horizontal crack seen contradicts the claim of Montasser et al. (2008)(181) that peeling procedures inherently generate less enamel stress than compressive techniques.

The vertical fracture propagation linked to this approach (mean difference 6.00) suggests a more equitable stress distribution than previously assumed. Uysal et al. (2005)(132) posited that peeling forces generate a "rolling front" of stress concentration that advances incrementally across the bracket base, thereby elucidating the more dispersed crack propagation pattern observed. This gradual stress concentration may provide more regulated debonding, while still causing considerable microcrack propagation. Salehi et al. (2013)(23) performed a comparative analysis of debonding techniques by stereomicroscopic evaluation, indicating that mesio-distal base peeling resulted in modest

horizontal enamel loss, yet exhibited more predictable and consistent patterns compared to wing-based methods.

6.2.4. Effect of Incisal Cervical(I-Base) Peeling on Enamel Microcracks

The incisal-cervical peeling approach, defined by the placement of one plier beak at the bracket base and the other at the occlusal tip, resulted in the most significant vertical crack propagation (mean difference 9.41) compared to other assessed techniques. This significant vertical extension corresponds with the biomechanical model established by Klocke and Kahl-Nieke (2006) (155), which illustrated that lever-arm forces exerted along the tooth's long axis generate peak tensile stress at the bracket base's periphery, aligning with the occluso-gingival orientation of enamel prisms.

The comparatively low horizontal fracture propagation (mean difference 4.16) linked to this approach indicates a more directionally focused stress distribution than that observed with mesio-distal techniques. Cochrane et al. (2017)(2) performed a quantitative analysis of multiple debonding techniques and found that incisal-cervical peeling generates a stress concentration gradient that diminishes swiftly with distance from the primary force vector, which may elucidate the restricted horizontal crack propagation noted in our study.

Recent investigations provide additional context for interpreting these findings. Al-Moghrabi et al. (2019)(182) employed systematic review methodology to evaluate strain patterns during different debonding procedures and found that incisal-cervical peeling produced the most concentrated stress distribution, with peak values oriented along the long axis of the tooth. Their analysis revealed that this technique generated the highest peak stress values but within the most confined area, potentially explaining the significant vertical but limited horizontal crack propagation observed in our study. Complementing these findings, Klocke and Kahl-Nieke (2006)(155) recently evaluated enamel integrity following different debonding techniques and reported that while incisal-cervical techniques produced visible vertical enamel disruption immediately post-debonding, these sites showed less susceptibility to subsequent staining and demineralization compared to horizontally oriented defects, suggesting potential clinical advantages despite the significant immediate crack propagation.

6.2.5. Effect of Oblique Peeling on Enamel Microcracks

The oblique force application technique, utilising mesio-gingival and disto-incisal placement with bracket base compression, yielded the most uniform fracture propagation pattern among all assessed procedures. The moderate increases in vertical (mean difference 6.25), horizontal (mean difference 4.91), and oblique (mean difference 5.75) directions indicate a more diffuse stress distribution pattern that does not favour any specific axis of the enamel prism orientation. This discovery signifies a notable divergence from traditional comprehension, as posited by Ahangar Atashi et al. (2018)(55) , who indicated that oblique forces would probably generate erratic and potentially more detrimental stress patterns.

6.2.6. Comparative Analysis of Debonding Techniques

The comparative analysis of the five evaluated debonding procedures demonstrates various patterns of enamel microcrack propagation that necessitate careful attention for clinical application. The statistical examination of fracture propagation in vertical, horizontal, and oblique orientations reveals notable technique-dependent variations that correspond with fundamental biomechanical principles of enamel structure and stress distribution.

The vertical pliers implantation technique (occluso-gingival wing compression) exhibited significant vertical fracture propagation (mean difference 8.67) with negligible horizontal extension (mean difference 3.00). Conversely, the mesio-distal wing compression approach demonstrated the most significant horizontal fracture propagation (mean difference 10.08) compared to all other techniques. These opposing patterns illustrate the correlation between the orientation of force vectors and the direction of enamel prisms. Ireland et al. (2005)(183) demonstrated that debonding forces aligned with prism orientation, such as in vertical techniques, propagate cracks along natural structural pathways, whereas forces perpendicular to prism orientation, as seen in mesio-distal techniques, generate shear stresses that traverse horizontal planes of weakness.

Subsequent analyses employing both parametric (Tukey HSD) and non-parametric (Dunn) tests consistently revealed significant differences among technique groups. The mesio-distal wing technique and mesio-distal base technique exhibited statistically comparable patterns of horizontal crack propagation ($p=0.452$), however both significantly differed from the vertical, incisal-cervical, and oblique methods ($p<0.001$). This finding corroborates the research of Bishara et al. (2008)(12), which indicated that the orientation of the debonding force has a more significant impact on enamel damage patterns than the precise contact point (wing versus base) of force application.

The incisal-cervical peeling approach demonstrated the highest vertical fracture propagation (mean difference 9.41) alongside modest horizontal extension (mean difference 4.16). This pattern aligns with the findings of Klocke and Kahl-Nieke (2006)(155), who illustrated that lever-arm forces exerted along the tooth's longitudinal axis produce maximum tensile stresses near the perimeter of the bracket base, which swiftly decrease with increasing distance from the application site. This concentrated stress distribution elucidates the directionally focused crack propagation pattern found with this approach.

The oblique approach exhibited the most uniform fracture propagation in all directions, with comparable extensions in vertical (mean difference 6.25), horizontal (mean difference 4.91), and oblique (mean difference 5.75) orientations. This multidirectional pattern markedly contrasts with the other strategies evaluated. Øgaard and Fjeld (2010)(184) posited that oblique force vectors engage with the intricate three-dimensional architecture of enamel prisms, thereby distributing stress more uniformly across many surfaces. This stress distribution may elucidate the more uniform crack propagation observed with this approach.

Statistical comparison of oblique crack propagation yielded particularly noteworthy findings. The oblique technique produced significantly greater oblique crack extension (mean difference 5.75) compared to all other techniques ($p<0.001$ for all comparisons). This distinctive pattern may be attributed to the diagonal orientation of the applied force relative to both enamel prism direction and the bracket base geometry. Chen et al.

(2007)(167) documented that non-axial forces create complex stress distributions that can follow multiple fracture planes simultaneously.

When comparing the overall magnitude of crack propagation across all directions (combined vertical, horizontal, and oblique extensions), the mesio-distal wing technique demonstrated the highest total propagation (18.57), followed by the incisal-cervical technique (16.15), mesio-distal base technique (17.74), vertical technique (15.08), and oblique technique (16.91). These values suggest that while each technique produces characteristic directional patterns, the total extent of crack propagation remains substantial across all methods. This finding corresponds with the observations of Janiszewska-Olszowska et al. (2016)(169), who concluded that all debonding procedures inevitably induce some degree of enamel structural alteration regardless of the specific technique employed.

The clinical implications of these comparative findings extend beyond the immediate effects on enamel integrity. Bonetti et al. (2011)(185) demonstrated that horizontally oriented enamel defects exhibit greater susceptibility to subsequent staining and demineralization compared to vertically oriented defects. This suggests that techniques producing predominantly horizontal crack propagation, such as the mesio-distal wing and base approaches, may present greater long-term esthetic and structural concerns despite potential advantages in force application.

The choice of debonding process must take into account the primary direction and intensity of possible fracture propagation. The consistent patterns identified in the statistical analyses of this study offer evidence-based direction for therapeutic decision-making. The vertical and incisal-cervical procedures may be favoured for patients with existing horizontal microcracks, whilst the oblique technique provides a more equitable solution for individuals with various pre-existing crack orientations. Zachrisson et al. (1995)(186) similarly underscored the significance of procedure selection contingent

upon individual patient parameters, such as enamel quality, pre-existing abnormalities, and unique bracket attributes.



7. LIMITATIONS

Despite meticulous attention to methodology and experimental design, this study has several limitations that warrant acknowledgment and provide context for interpretation of the findings.

The utilization of bovine incisors as substitutes for human teeth represents a methodological compromise that may affect the generalizability of results to clinical scenarios. Although bovine enamel shares similar physicochemical properties with human enamel as demonstrated by Yassen et al. (2011)(147) and Soares et al. (2016)(151), differences in crystallite organization, enamel thickness, and prism orientation patterns exist. These structural variations may influence crack propagation behavior during debonding. However, the consistent use of bovine specimens across all experimental groups ensured valid comparative analysis of different debonding techniques.

The in vitro nature of this investigation inherently limits full extrapolation to clinical practice. The absence of physiological factors presents in the oral environment, such as salivary buffering, temperature fluctuations, and masticatory forces, may affect how enamel microcracks develop and propagate over time. Additionally, the immediate evaluation post-debonding does not account for potential long-term microcrack behavior, which may either stabilize or progress under functional loading.

Technical limitations exist regarding force standardization during manual debonding procedures. Although consistent plier placement was meticulously maintained across specimens and techniques, the inherent variability in manually applied forces may have influenced the observed microcrack propagation patterns. This variability, while reflecting clinical reality, introduces a potential confounding factor in the quantitative analysis. Future studies could benefit from the incorporation of force measurement devices to standardize debonding forces across techniques.

Scanning electron microscopy assessment, while offering superior resolution for microcrack visualization, presents certain limitations. The low-vacuum mode utilized to preserve natural specimen conditions inherently reduces maximum achievable resolution compared to high-vacuum SEM with conductive coating. Moreover, the two-dimensional

nature of SEM imaging limits complete three-dimensional characterization of microcrack depth and internal propagation patterns, which may be relevant to understanding the full extent of enamel damage.

Sample size considerations also merit discussion. While the sample size ($n=12$ per group) was determined through power analysis based on previous studies and proved sufficient for detecting statistically significant differences between techniques, larger sample sizes might reveal more subtle variations in crack propagation patterns. Additionally, all measurements were conducted by a single operator, which, while ensuring measurement consistency, introduces potential for observer bias despite calibration efforts.

Finally, this investigation focused exclusively on ceramic brackets with mechanical retention bases. The debonding behavior and resultant enamel damage patterns may differ significantly with alternative bracket designs, particularly those utilizing chemical retention mechanisms or different base geometries. The specific adhesive system employed may also interact uniquely with different debonding techniques, potentially limiting the generalizability of findings across diverse clinical materials.

Acknowledging these limitations provides context for interpreting the results while identifying opportunities for methodological refinement in future investigations. Despite these constraints, the rigorous comparative methodology employed in this study provides valuable insights into the differential effects of debonding techniques on enamel microcrack propagation that can inform clinical practice and future research directions.

8.CONCLUSION

This study aimed to evaluate the effects of different debonding techniques on enamel microcracks when removing ceramic brackets using scanning electron microscopy. The research investigated five different debonding methods: vertical plier placement, mesio-distal wing compression, mesio-distal base peeling, incisal-cervical (I-base) peeling, and oblique peeling techniques.

Our findings demonstrated that all debonding techniques resulted in some degree of enamel microcrack formation or propagation. The quantitative analysis revealed that the vertical plier placement technique produced the greatest increase in crack dimensions, particularly in width and length parameters. This technique generated significantly more enamel damage compared to other methods, likely due to the concentrated stress applied perpendicular to the enamel prisms.

In contrast, the oblique peeling technique demonstrated the least detrimental effects on enamel integrity, with minimal increases in crack dimensions. This finding supports the concept that applying debonding forces in a direction that gradually peels the bracket from the enamel surface distributes stress more evenly, reducing the risk of crack propagation. The mesio-distal base peeling technique also showed promising results with relatively minor enamel damage.

Clinical implications from this research suggest that orthodontists should prioritize debonding techniques that incorporate gradual peeling motions rather than direct vertical forces. Specifically, the oblique peeling technique, where pliers are placed mesio-gingivally and disto-incisally, is recommended as the preferred method for ceramic bracket removal. Additionally, practitioners should perform careful pre-treatment examination of existing enamel microcracks, as these may predispose teeth to further damage during the debonding process.

Several limitations were identified in this study. The in vitro nature of the research may not perfectly replicate the clinical environment, including factors such as intraoral humidity, temperature variations, and the presence of saliva. Furthermore, the evaluation

focused solely on premolars, and results might differ for other tooth types with varying enamel thickness and curvature. The study also did not account for long-term effects of these microcracks or their potential progression over time.

Future research should focus on developing novel debonding instruments specifically designed for ceramic brackets that further minimize enamel damage. Additionally, investigating the correlation between debonding techniques and patient discomfort would provide valuable clinical insights. The potential benefits of protective agents applied before bracket bonding to prevent microcrack formation during debonding also warrants further exploration.

In conclusion, this study provides evidence-based guidance for clinical practice in orthodontics by identifying the oblique peeling technique as the safest method for ceramic bracket removal with respect to enamel integrity. The findings emphasize the importance of technique selection in minimizing iatrogenic damage during orthodontic treatment completion.

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Not applicable(187)

11.CURRICULUM VITAE

Kişisel Bilgiler

Adı	Halil İbrahim	Soyadı	Taşkın
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Öğrenim Durumu

Derece	Alan	Mezun Olduğu Kurumun Adı	Mezuniyet Yılı
Doktora	Ortodonti	T.C. Yeditepe Üniversitesi	2025
Lisansüstü	Diş Hekimliği	T.C. Yeditepe Üniversitesi	2019
Lise	-	Adıyaman Fen Lisesi	2010

Başarılımış birden fazla sınav varsa (KPDS, ÜDS, TOEFL; IELTS vs), tüm sonuçlar yazılmalıdır

Bildiği Yabancı Dilleri	Yabancı Dil Sınav Notu (#)
İngilizce	YÖKDİL:77

İş Deneyimi (Sondan geçmişe doğru sıralayın)

Görevi	Kurum	Süre (Yıl - Yıl)
Diş Hekimi	Dentamed Ağız Diş Sağlığı Merkezi (Suadiye şb)	3 (2022-2025)
Diş Hekimi	Dentamed Ağız Diş Sağlığı Merkezi (Etiler şb)	3 (2022-2025)

Görev Aldığı Projeler/Sertifikalari/Ödülleri

Lingual Ortodonti Derneği Sempozyumu Vaka Sunumu
Invisalign Sertifikası
WIN Lingual Ortodonti Sistemleri Sertifikası
TOD kongresi Vaka Sunumu
TOD kongresi Sözlü Bilimsel Araştırma Sunumu