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Evaluation of Enamel Surface Roughness After Laser Removal of Clear Aligner Attachments

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EVALUATION OF ENAMEL SURFACE ROUGHESS AFTER LASER REMOVAL OF CLEAR ALIGNER ATTACHMENTS

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A Thesis Presented to the Faculty of the College of Dental Medicine of

Nova Southeastern University in Partial Fulfillment of the Requirements for the

Degree of

MASTER OF SCIENCE

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I certify that I am the sole author of this thesis, and that any assistance I received in its preparation has been fully acknowledged and disclosed in the thesis. I have cited any sources from which I used ideas, data, or words, and labeled as quotations any directly quoted phrases or passages, as well as providing proper documentation and citations. This thesis was prepared by me, specifically for the M.Sc. degree and for this assignment.

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DEDICATION

I would like to dedicate this thesis to all of my family and friends who have supported me throughout my life and education. Additionally, this thesis is also dedicated to my orthodontic faculty, who have devoted endless hours of knowledge to the advancement of my education at Nova Southeastern University. Lastly, I would also like to dedicate this work to my co-residents who were instrumental in helping me challenge myself to strive to become the best orthodontist possible.

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To Christina and Gizmo. You have been the biggest support in my residency. There is no way I could have completed this journey without you both. Thank you for your unconditional love.

ABSTRACT

EVALUATION OF ENAMEL SURFACE ROUGHESS AFTER LASER REMOVAL OF CLEAR ALIGNER ATTACHMENTS

DEGREE DATE: December 2018

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COLLEGE OF DENTAL MEDICINE, NOVA SOUTHEASTERN UNIVERSITY

Thesis Directed By: Sergio Real, D.D.S., M.S., Committee Chair

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Introduction: Following orthodontic appliance removal, the primary objective is to remove all remaining adhesive from the facial surfaces and return the enamel to its pretreatment state. Composite remnant removal must be performed with as little to no damage to the superficial layer of enamel to ensure long-term health and esthetics of the dentition. Numerous studies have investigated the efficacy of multiple composite remnant removal methods with no consensus as to which method should be the standard of care[1-7]. Traditional methods of composite removal after bracket debonding have included tungsten-carbide burs, white stone burs, green stones, and composite discs; which all damage the enamel surface to some degree. Technological advances in the last decade have allowed for the use of lasers to be incorporated into the field of dentistry. Very few studies have evaluated the prospect of using Nd:YAG, CO2, and Er:YAG laser for composite removal following orthodontic bracket debonding but no studies have investigated these methods for clear attachment removal. Therefore, the goal of this research study was to evaluate the effectiveness of Er:YAG laser to remove clear aligner attachments. **Methods:** Forty freshly extracted human premolars were randomly divided into four groups (one control group and three experimental groups). Prior to experimentation, the sample teeth had a portion of the buccal enamel surface flattened to normalize the surfaces. Pre-treatment enamel surface roughness value (Ra) was measured using the Veeco DEKTAK 150 stylus profilometer, pre-treatment surface gloss (degrees) was measured using the Novo-Curve Glossmeter, and pre-treatment enamel surface morphology was analyzed using the Olympus SZX7 stereomicroscope. Clear aligner attachments were bonded to the sample teeth using the small wire bonder Mini Mold attachment. In the control group, clear aligner attachment removal was completed using a multi-fluted tungsten carbide bur with high-speed handpiece. In experimental group 1, clear aligner attachment removal was completed using Er:YAG laser at 215 mJ/30 Hz/6.45 W. In experimental group 2, clear aligner attachment removal was completed using Er:YAG laser at 300 mJ/20 Hz/6W. In experimental group 3, clear aligner attachment removal was completed using Er:YAG at 240 mJ/20 Hz/4.8 W. Pulp temperature changes during clear aligner attachment removal was measured using a K-type thermocouple. Surface roughness, surface gloss, and morphology were also be examined following clear aligner attachment removal. **Results:** Post hoc analyses using the Tukey HSD post hoc criterion for significance indicated that the average roughness score was significantly lower before treatment than the control group ($p < 0.001$), experimental group 1 ($p < 0.001$), experimental group 2 ($p < 0.001$), and experimental group 3 ($p < 0.001$). It was also noted that the average roughness score was significantly

lower in the control group (M = 2.77, SD = 1.18) when compared to the three experimental groups. Post hoc analyses using the Tukey HSD post hoc criterion for significance indicated that the average gloss was significantly lower in the control (M = -5.93, SD = 1.67) than experimental group 1 (M = -12.25, SD = 3.39, $p < 0.001$), experimental group 2 (M = -13.36, SD = 3.12, $p < 0.001$) and experimental group 3 (M = -11.89, SD = 2.03, $p = 0.001$). Post hoc analyses using the Tukey HSD post hoc criterion for significance indicated that the average temperature was significantly lower in the control group (M = 1.58, SD = 0.53) and experimental group 2 (M = 1.49, SD = 0.29) than experimental group 1 ($p = 0.006$) and experimental group 3 ($p = 0.001$). **Conclusions:** All four clear aligner attachment removal methods significantly increased the enamel surface roughness and decreased gloss; however, the multi-fluted tungsten-carbide bur provided the least amount of unwanted side effects on enamel surface roughness, morphology, and gloss. The multi-fluted tungsten-carbide bur and Er:YAG laser can both safely remove clear aligner attachments with very little to no risk of pulpal necrosis.

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Chapter 1: Introduction

1.1 Background on Orthodontic Debonding

After debonding orthodontic brackets, residual composite is commonly present on the facial surfaces of the dentition. The primary objective following orthodontic debonding is to remove the remaining composite from the buccal surfaces and restore the teeth as close to their original state prior to treatment without any significant damage. Preserving the condition of the superficial layer of enamel is of great importance because this layer consists of the greatest fluoride and mineral content compared to deeper layers[1,2]. Iatrogenic damage to the enamel surface also increases the surface roughness leading to increased retention of bacterial plaque and increased risk of decalcification. In addition, compromising the outermost enamel surface can reduce the aesthetic appearance of the teeth. In many clinical studies, enamel fracture following debonding of orthodontic brackets has been described with an increased incidence of damage in ceramic brackets compared to metal brackets[3,4].

1.2 Debonding Methods

Past investigators have explored different removal methods of residual composite following orthodontic treatment, however, there is no agreement as to which method is the most safe and efficient[5, 6, 7, 8, 9]. *Mohebi et al* concluded that the tungsten carbide bur is most efficient when removing composite remnants on extracted premolars when compared to white stone bur, tungsten carbide bur, and tungsten carbide bur with loupe magnification[6]. *Khatria et al* concluded that Super Snap discs restored the enamel surface closest to its original state when removing surface composite[10]. In 2014, *Tonetto et al* performed a literature review of the various ways to remove composite resin following orthodontic debonding only to conclude that there is no clear consensus among orthodontists as to which removal method is most efficient[8].

Complete removal of composite is necessary because residual surface composite contributes to the accumulation of plaque, staining, and the formation of white spot or carious lesions[11]. Finding the most safe and efficient method to remove composite remnants is important to return teeth to their pretreatment state and preserve their original biology without compromise.

To date, few studies have been performed evaluating the efficacy of lasers as an alternative to traditional methods (high-speed handpiece with various burs) for the removal of remaining composite after orthodontic debonding. The previous studies that have investigated this topic specifically evaluated the following laser types and parameters: Q-switched Nd:YAG with a wavelength of 355 nm[12], CO_2 laser operating at 9.3 mm with high pulse repetition rates[13, 14, 15], 30 W diode-pumped Er:YAG laser[16], and Er:YAG laser at a wavelength of 2.94 μm[17]. *Gomez et al* found that on-line Nd:YAG laser radiation can remove adhesives on enamel surfaces with no evidence of damage[12]. *Chan et al* concluded that CO_2 laser can be successfully used to remove surface composite with minimal enamel loss[13, 14]. *Yassaei et al* found that Er:YAG laser can successfully remove surface composites but can also cause irreversible damage[17]. All of these studies evaluated one laser type with only one parameter setting versus a traditional method(s) of composites removal such as tungsten-carbide bur, white stone bur, etc.

1.3 Clear Aligners

The idea of the clear aligner was introduced in 1945 by H.D. Kesling through his "tooth positioner"[18]. This appliance was made of rubber and meant to make minor corrections to the position of the teeth immediately following orthodontic appliance removal. In 1971, Ponitz introduced vacuum-formed retainers to replace the traditional Hawley appliance as a cheaper and more esthetic retention option[19]. These retainers were able to perform minor tooth movements, refinements, and treat minor relapses post-treatment. In 1993, Sheridan created his own clear aligner system, the Essix Aligner, which was intended to perform minor corrections in anterior teeth through a series of thermoplastic trays[20]. In his cases, Sheridan's series of thermo-formed plastic clear aligners validated that a clear aligner can promote minor tooth movement. In 1997, two MBA students at Stanford University (Chisti and Wirth) created Align Technology and popularized the use of this new technology in North America. In the last decade, the use of clear aligners as opposed to traditional orthodontic appliances has exploded with millions of patients worldwide using this treatment modality. The big clear aligner companies are beginning to market clear aligner treatment in stores and shopping malls as "consumer products". According to their website, Invisalign claims that they have successfully treated over 6 million patients with clear aligners without the need of traditional orthodontic appliances. With aligner therapy being in popular public demand, composite attachments on the facial surfaces of the teeth are bonded for biomechanical purposes in the majority of cases.

1.4 Light Amplification by Stimulated Emission of Radiation

The basis of light amplification by the stimulated emission of radiation (or laser) was first described by Albert Einstein in 1916 in his theory of stimulated emission[21]. In this theory, a charged photon of a specific frequency comes into contact with an excited atomic electron, which causes the electron to fall into a lower energy level. In 1958, Charles Townes and Arthur Schawlow published a paper on laser theory that described how a laser could be built which caused the scientific world in a frenzy to make this theory a reality[22]. In 1960, Theodore Maiman constructed the ruby laser, which is considered to be the first successful light laser[23].

Lasers operate through the conversion of electrical energy into a high-density energy via stimulation and amplification processes. Through this stimulation process, electrons in some sort of medium are excited leading to the emission of photons. One of four processes can occur when a laser photon interacts with a substrate: 1. Destruction or cutting of hard and soft tissues occurs by absorbance of the photons by the target[24]. 2. Reflection or deflection of the energy at the photon/target interface. 3. The photons scatter in multiple directions as they enter the substrate. 4. There is no interaction between the photons and substrate[25]. Four major types of lasers exist and they are classified by their lasing medium, which can be gas, liquid, solid, or semiconductor.

Gas lasers function by discharging an electric current through a gas (usually helium, carbon dioxide, or a mixture of helium and neon) within the laser medium to produce laser light. Gas lasers are typically the most powerful lasers and are used to cut hard tissues. Liquid lasers create laser light from the excitation of the organic dye used as the lasing medium[26]. Since a wide variety of dyes can be used for this laser type, a wide range of wavelengths can be produced. Liquid lasers are commonly used in medicine for the treatment of kidney stones as well as tattoo removal. Solid-state lasers use solid or crystalline mediums that get excited to higher energy states via a pumped electrical current. Erbium, neodymium, and chromium ions are most commonly used as the active medium. This type of laser is commonly used in military weaponry, engineering, and dentistry. The development of laser technology has been revolutionary in engineering and has become increasingly popular in the biomedical and dental sciences in the last couple decades.

1.5 Lasers in Dentistry

The use of laser or "light amplification by the stimulated emission of radiation" in the field of dentistry has exploded in the last decade with many different clinical applications[27]. The most commonly used lasers in dental practice include the Nd: YAG (neodymium yttrium aluminum garnet), Er: YAG (erbium yttrium aluminum garnet), CO_2 (carbon dioxide), and diode lasers. Studies have shown that when laser radiation is applied to tooth surface, the energy is absorbed into the hard tissue surface and converted into heat[28]. The clinical applications for lasers include: non-surgical sulcular debridement for control of periodontal disease[7], removal of faulty composite restorations[29], cavity preparations[30] , crown preparations, soft tissue ablation/gingivectomy[30], frenectomy, crown lengthening, bacterial disinfection[33], and pain control. In the field of orthodontics, laser has been used for enamel etching, debonding of brackets, and acceleration of tooth movement[31]. The use of laser to potentially remove remaining composite after bracket debonding could be a useful alternative if selective removal of composite is possible without damaging the underlying enamel.

1.6 Er:YAG Laser

The erbium yttrium aluminum garnet (Er:YAG) laser is a solid-state laser, with erbium as its active medium, that was first conceptualized by *Zharikov et al* in 1975[31]. Zharikov's team found that they could stimulate emissions from erbium ions in crystallized yttrium, aluminum, and garnet; which paved the way for today's version of this laser. In 1992, the first Er:YAG laser on the market for dentists was introduced by KaVo. The Er:YAG laser emits infrared light with a wavelength of 2940nm which is also the maximal wavelength absorption of water[32]. Since the output beam of this laser is strongly absorbed by water, the target substrate should contain a high water content[33]. Hydroxyapatite is very well hydrated, so this laser is ideal for cutting teeth and bone; which is why it is commonly used in medical and dental practices. During hard tissue ablation, the superficial most layer of the enamel or dentin is heated until the substrate's strength is exceeded[34]. The overheated dental material and irrigation vaporizes eliminating the broken dental fragments allowing for ablation of the next dental layer. Laser technology has tremendously evolved since this time and modern-day lasers are adjustable so that the operator can specify how much energy (ranging from 100 to 1000 mJ) to be used in a given procedure[35]. The frequency of pulsations can also be adjusted promoting either slow or fast removal of substrate.

1.7 Effects of Temperature on Pulp

Studies have shown that when laser radiation is applied to tooth surface, the energy is absorbed into the hard tissue surface and converted into heat. *Zach et al* investigated the effect of temperature rise in the pulp chambers of teeth and found that an increase of 5.5ºC caused pulpal necrosis in 15% of the tested teeth[36]. Consequently, when the pulpal temperature was increased by 11ºC, approximately 60% of the teeth underwent pulpal necrosis. Lastly, when the pulpal temperature was increased by 17ºC, 100% of the teeth underwent pulpal necrosis. This study showed that there is a positive correlation between the amount of applied external head and the death of the dental pulp.

Overheating the vital tissues in the pulp chamber leads to an infiltration of inflammatory markers that can be seen histologically[37]. More specifically, there is an influx of lymphocytes, macrophages, plasma cells and other inflammatory mediators, which increases the intrapulpal pressure constricting the blood vessels. This constriction of the vasculature leads to cellular death or necrosis of the tissue.

Multiple studies show that lasers can generate pulpal heat increases that can remove enamel safely without irreversible pulp damage[7, 38, 39, 40]. *Yassaei et al* evaluated the use of Er:YAG laser versus composite burs in removing surface composites and concluded that the composite burs generated higher, but safe, pulpal temperature increases compared to the Er:YAG laser[7]. *Staninec et al* investigated the pulpal effects of enamel ablation with CO2 laser (36 J) and concluded that the intrapulpal temperature rises were within a safe range[38]. *Oelgiesser et al* investigated the effect of Er:YAG laser on pulpal temperature during cavity preparation and concluded that all pulp temperature rises were under 5.5ºC[39]. *Calvacanti et al* compared pulpal temperature increases between Er:YAG laser (350 mJ) and high-speed handpiece with tungsten-carbide bur during enamel ablation concluding that similar, safe temperature increases occurred with each ablation method[40].

1.8 Purpose

Clear aligner therapy has become increasingly popular in the last decade for patients seeking esthetic orthodontic treatment. The majority of clear aligner companies require that composite-based attachments be placed on the facial surfaces of the teeth, which are to be removed at the end of treatment. The purpose of this study was to determine if laser can be used as a safe alternative to remove clear aligner attachments with little to no undesired effects to enamel surface and pulp chamber.

To date, this study was the first study to evaluate the effectiveness of laser removal of composite-based clear aligner attachments. In addition, this study was the first to investigate how multiple different laser settings affect the most superficial layer of enamel as well as their effects on the pulp. If laser removal of composite attachments after clear aligner therapy is more efficient than traditional methods, orthodontists could adopt this method to safely return the patients enamel back to its pretreatment state while preserving their original biology.

1.9 Specific Aims

Specific Aim 1: To evaluate the difference in enamel surface roughness after clear aligner attachment removal using multiple laser settings.

Specific Aim 2: To evaluate the difference in enamel surface gloss measurement after clear aligner attachment removal using multiple laser settings.

Specific Aim 3: To compare enamel surface morphological changes after each clear aligner attachment removal method.

Specific Aim 4: To compare pulpal temperature change with each laser setting during clear aligner attachment removal.

1.10 Hypotheses

H_0 *1*: There is no difference in enamel surface roughness after clear aligner attachment removal using multiple laser settings.

H_0 *2*: There is no difference in enamel surface gloss measurement after clear aligner attachment removal using multiple laser settings.

H_0 *3*: There is no difference in enamel surface morphology after each clear aligner attachment removal method.

H_0 *4*: There is no difference in pulpal temperature change with each laser setting during clear aligner attachment removal.

1.11 Location of Study

This study was designed and carried out in the research lab at:

Nova Southeastern University, College of Dental Medicine

3200 S University Drive

Fort Lauderdale, Florida 33328

Chapter 2: Materials and Methods

2.1 Design Overview

The material for this study consisted of 40 freshly extracted human first premolars; maxillary and mandibular. The extracted teeth were obtained from the post-graduate Periodontics and OMFS departments at the Nova Southeastern University College of Dental Medicine. The sample of 40 premolars were randomized into one control group and three experimental groups of ten to be tested by each attachment removal method (see figure 1). In the control group, clear aligner attachment removal was completed using a multi-fluted tungsten carbide bur (Komet USA, Rock Hill, SC, Catalog #H48LQ.FG.014) with high-speed handpiece. In experimental group 1, clear aligner attachment removal was completed using Er:YAG laser at 215 mJ/30 Hz/6.45 W. In experimental group 2, clear aligner attachment removal was completed using Er:YAG laser at 300 mJ/20 Hz/6 W. In experimental group 3, clear aligner attachment removal was completed using Er:YAG at 240 mJ/20 Hz/4.8 W. The laser settings used in this were chosen (along with consultation from Dr. Jeff Shiffman) based off composite removal efficacy on bovine teeth in a pilot study. Complete clear aligner attachment removal with no undesired effects on the enamel surface or pulp chamber would be considered to be an ideal result in this study.

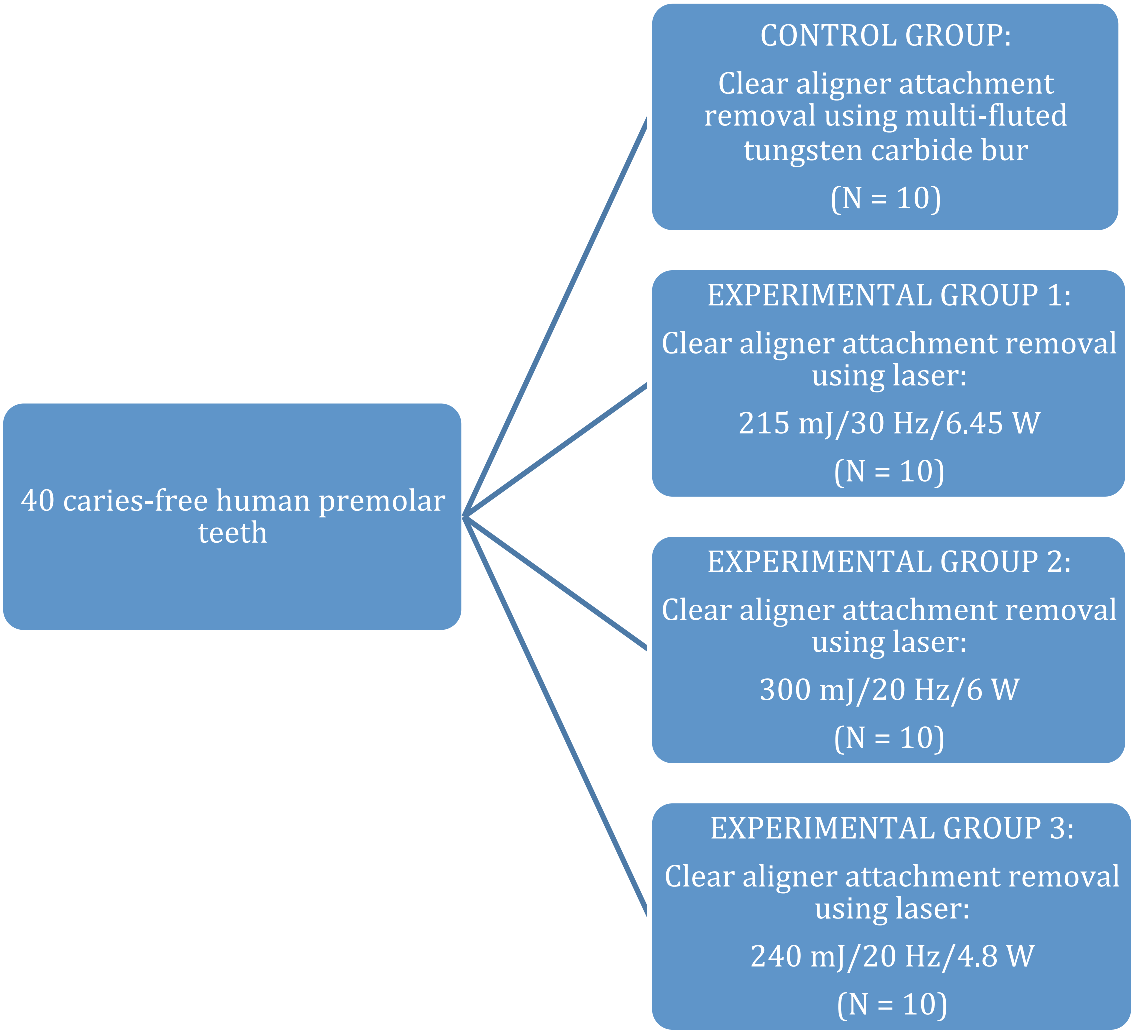


Figure 1. Study design

2.2 Clear Aligner Attachment

The small wire bonder Mini Mold attachment (Ortho Arch, Schaumberg, IL) was using as the clear aligner attachment template for this study. This allows for the operator to bond reproducible attachments to each sample tooth. The dimensions of the small wire bonder attachment are: 2mm diameter and 1.5mm height.

Figure 2. Small wire bonder mini mold attachment

2.3 Sample Preparation

In this *in vitro* experimental study, forty human first premolars extracted for orthodontic or periodontal indications were evaluated prior to inclusion. The inclusion criteria of the extracted teeth were that the teeth were free of visible caries, free of enamel defects or white spot lesions that could lead to compromised bonding of attachments, and intact buccal surfaces. Teeth were excluded from the sample if they were cracked or fractured during extraction. The teeth were debrided of any remaining tissue and stored in a room temperature solution of 0.1% (weight/volume) thymol in distilled water prior to bonding for ten days to inhibit growth of bacteria and prevent dehydration[1]. All specimens were labeled with nail polish (Figure 3) so that each tooth could be identified after clear aligner attachment removal.

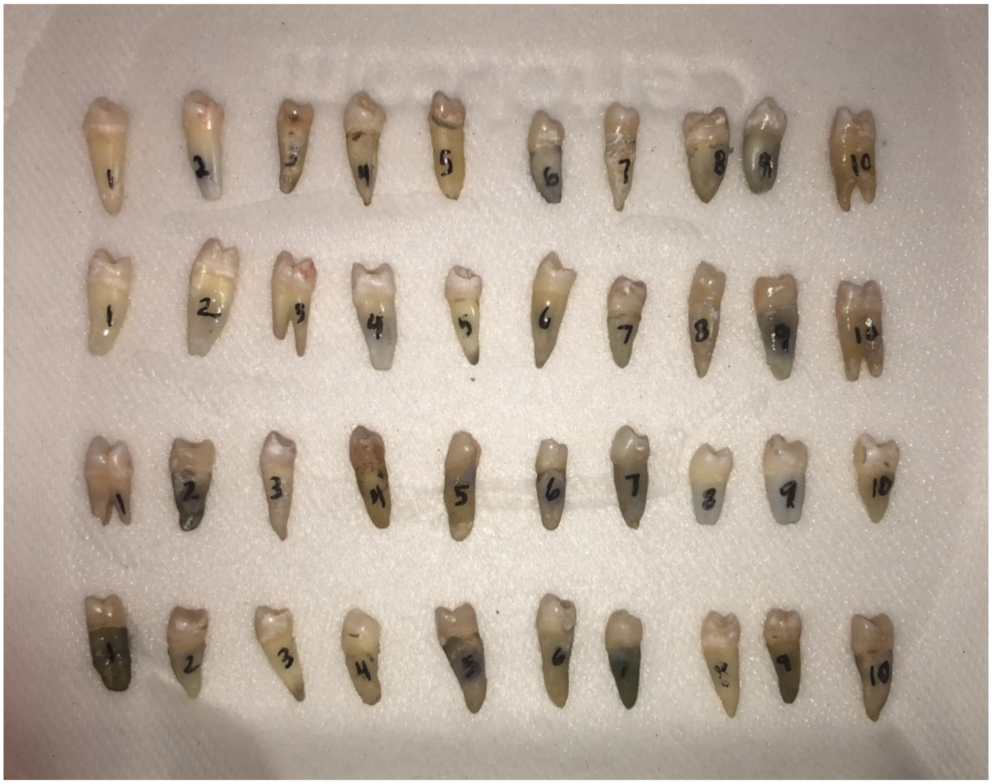


Figure 3. Extracted human premolars (n=40).

The extracted teeth then had a portion of the buccal enamel surface flattened using a Metaserv 2000 grinder/polisher (Figure 4) to remove the contours of the teeth. This was done to normalize the buccal surfaces of the teeth to remove any anatomic variation. The specimens were first flattened with a grit of 320 then polished with a grit of 600 (Figure 5). The sample teeth were flattened cautiously so no dentin was exposed and that the entire clear aligner attachment could be bonded (Figures 6 and 7).

Figure 4. Metaserv 2000 grinder/polisher

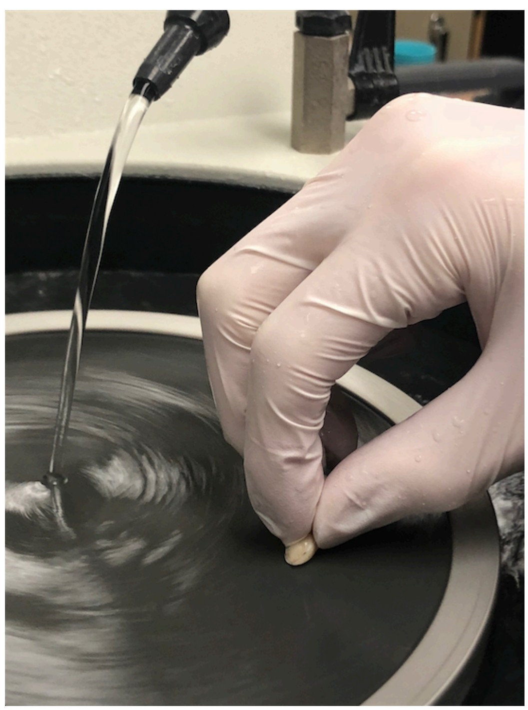


Figure 5. Buccal surface of premolar being flattened and polished

Figure 6. View of flattened enamel surface from mesial-distal view

Figure 7. View of flattened enamel surface from facial view

In preparation for the bonding of the clear aligner attachments to the extracted premolars, each sample tooth was cleaned with non-fluoridated pumice for 10 seconds then thoroughly rinsed with a water spray and dried for 10 seconds with an oil-free air syringe (Figure 8).

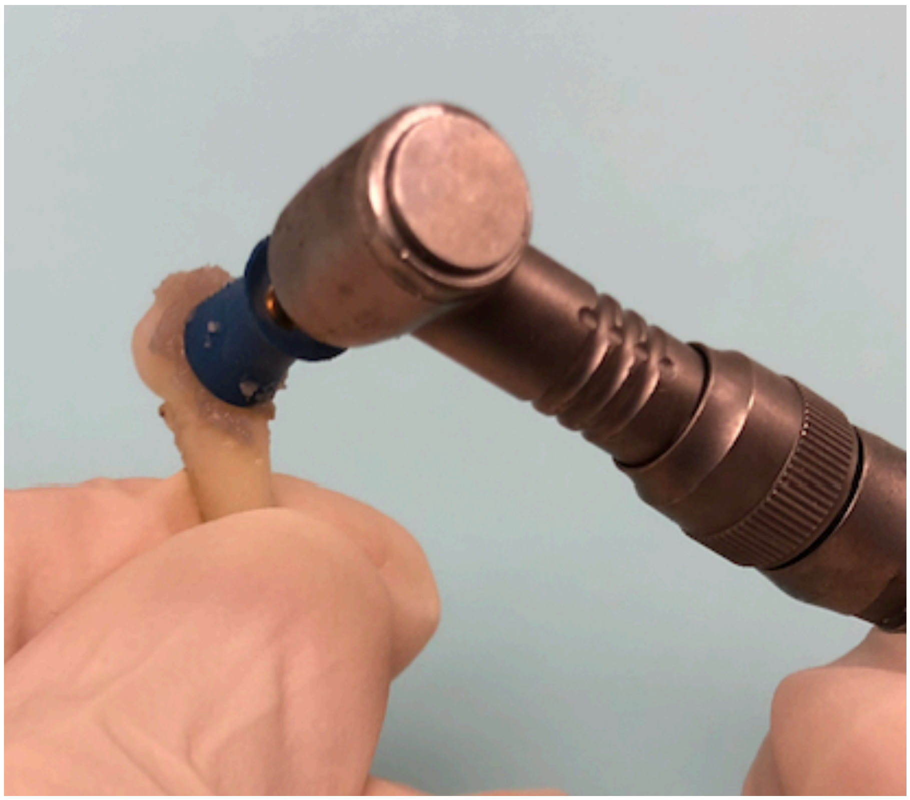


Figure 8. Sample tooth being cleaned with pumice

To prepare the teeth for pulpal temperature change assessment during attachment removal, a small access hole was drilled on the lingual aspect of each tooth at the level of the cementoenamel junction giving access to the pulpal chamber (Figure 9).

Figure 9. Lingual pulpal access hole

2.4 Pre-treatment Measurements

Prior to any experimentation, one randomly selected tooth from each test group (four total) and a baseline enamel surface roughness value (Ra) was measured using the Veeco DEKTAK 150 stylus profilometer (Bruker Corp, Billerica, MA) (Figure 10). Previously known as Arithmetic Average or Center Line Average, Ra is universally recognized today and is the international parameter of roughness. The profilometer was calibrated according to the manufacturer's instructions before the surface roughness of each tooth was measured. A roughness measurement (μm) was made in 3 different sites of each randomly selected sample tooth and an average was calculated. This calculated average represented the baseline enamel surface roughness of all sample teeth. The sample teeth were mounted on a glass slide with sticky wax for the measurements (Figure 11).

For pre-treatment morphological assessment, the initial enamel surface topography of each sample tooth was evaluated using stereomicroscopy at a magnification of 10 X and 25X. The Olympus SZX7 stereomicroscope (Olympus, Ceter Valley, PA) was used in this study (Figure 12). The sample teeth were mounted on a glass slide with sticky wax for surface topography assessment (Figure 11).

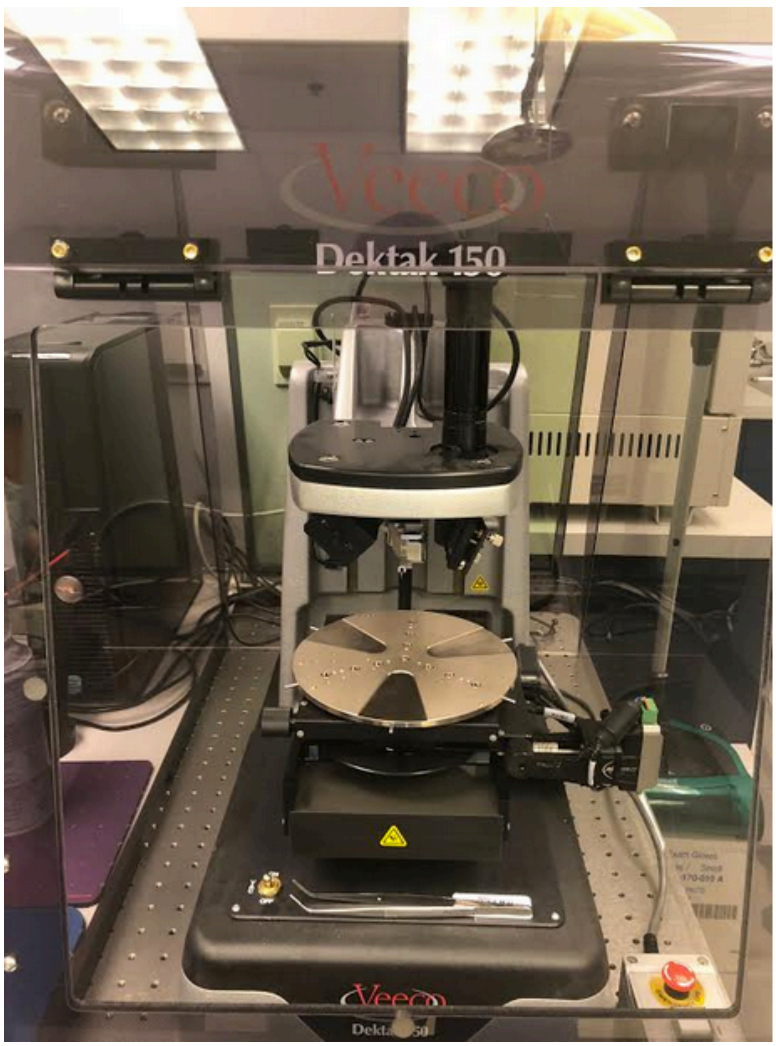


Figure 10. Veeco DEKTAK 150 stylus profilometer

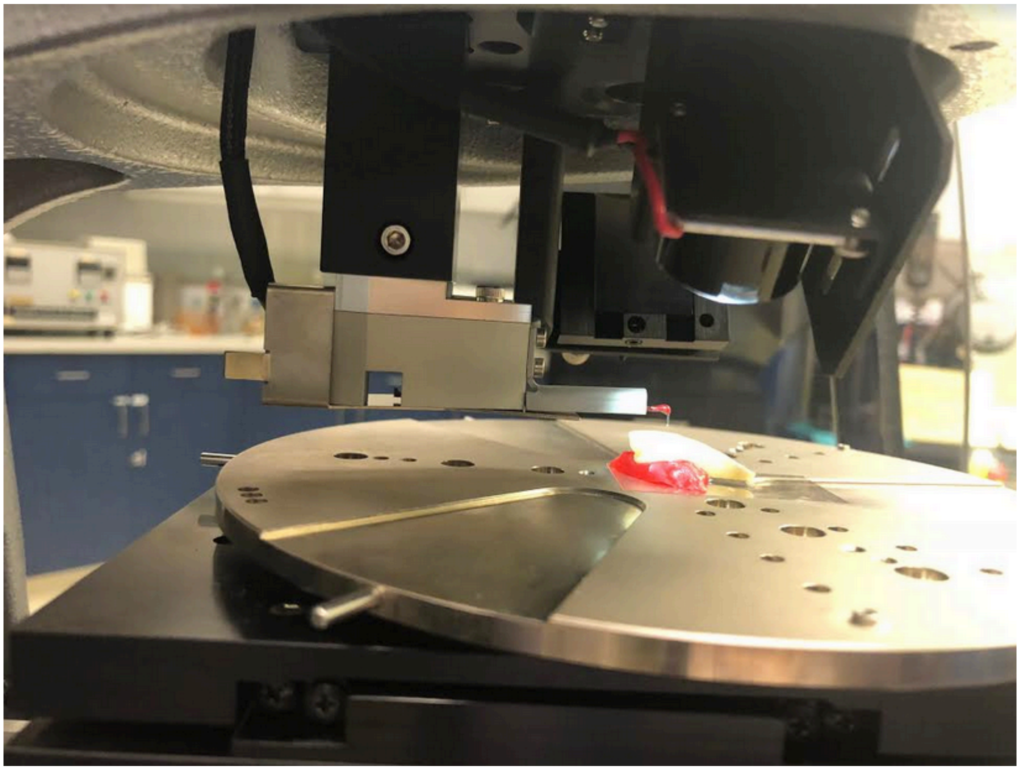


Figure 11. Sample tooth mounted on profilometer

In order to evaluate enamel surface gloss, an initial surface gloss measurement was measured using the Novo-Curve Glossmeter (Rhopoint Instruments, Hastings, UK) (Figure 12). This surface gloss measurement is noted as the angular selectivity of reflectance involving surface-reflected light and quantifies esthetic surface appearance. This variable was measured in degrees. The sample teeth were mounted on a glass slide with sticky wax so that the flattened buccal surface of the sample teeth was parallel and facing downward towards the aperture of the glossmeter (Figure 13). The mounted tooth was completely covered using an opaque shield to prevent any ambient light from affecting the reading. The initial gloss of every sample tooth was measured and the glossmeter was re-calibrated between each measurement.

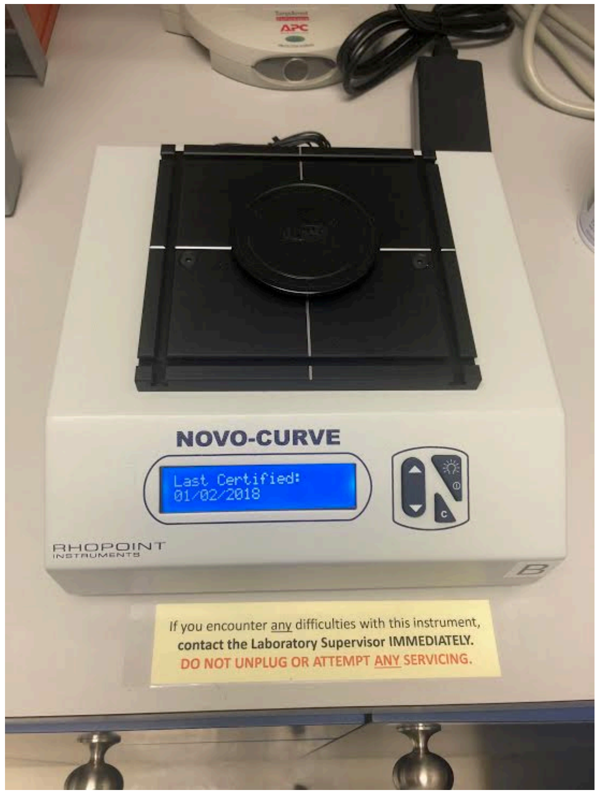


Figure 12. Novo-Curve glossmeter

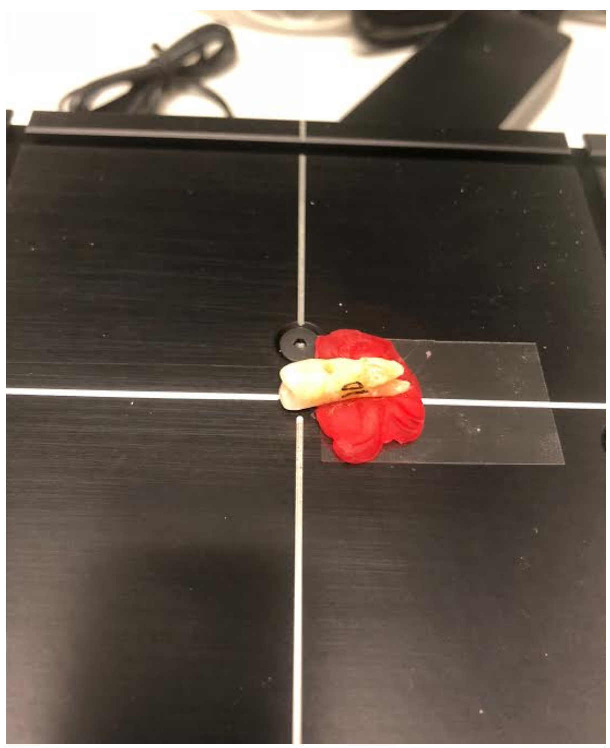


Figure 13. Sample tooth mounted on glossmeter

For pre-treatment morphological assessment, the initial enamel surface topography of each sample tooth was evaluated using stereomicroscopy at a magnification of 10 X and 25X. The Olympus SZX7 stereomicroscope (Olympus, Ceter Valley, PA) was used in this study (Figure 14). The sample teeth were mounted on a glass slide with sticky wax for surface topography assessment (Figure 15).

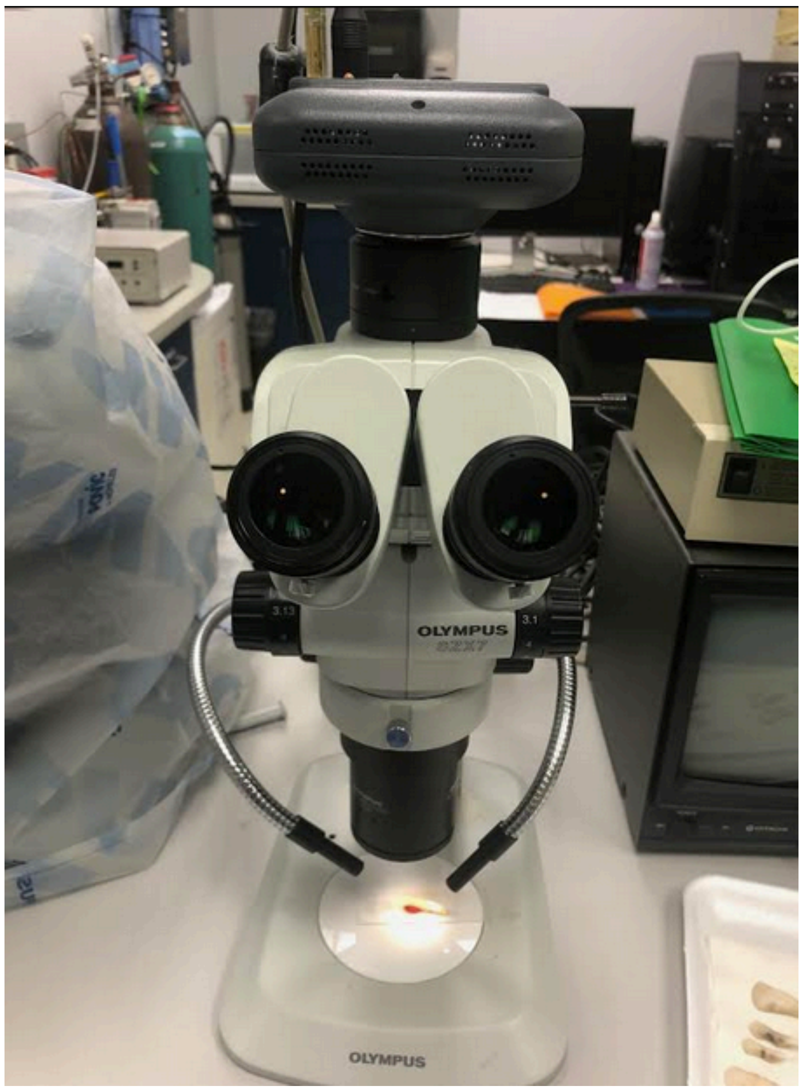


Figure 14. Olympus SZX7 stereomicroscope

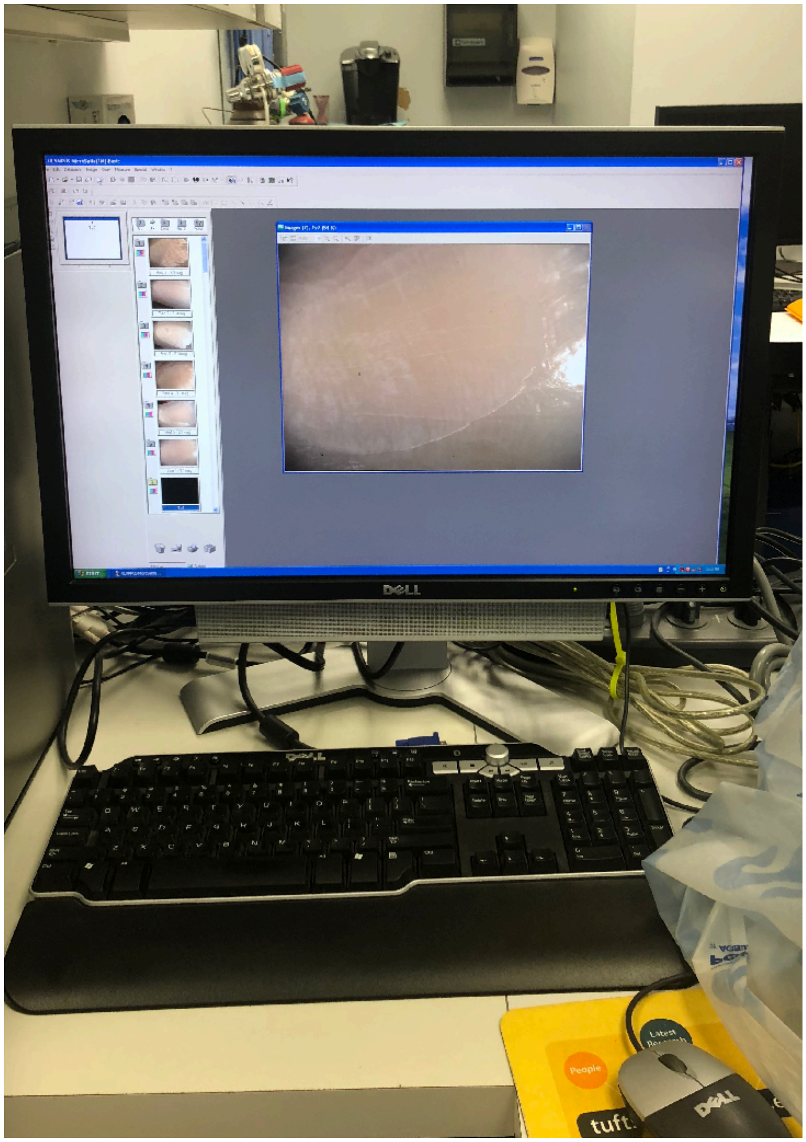


Figure 15. Sample tooth mounted on glossmeter

2.5 Bonding of Clear Aligner Attachments

In preparation for the bonding of clear aligner attachments, the sample teeth were then etched using 37% phosphoric acid gel (3M Unitek) for 30 seconds, rinsed thoroughly with water spray for 10 seconds, and then dried for 10 seconds with an oil-free air source. Following rinsing and drying, the enamel surfaces displayed a white, chalky appearance (Figure 16). Following manufacturer instructions, Assure Plus adhesive bonding agent (Reliance Orthodontic Products, Itasca, IL) was then applied onto the enamel surface in a thin coat and be left undisturbed for 5 seconds (Figure 17). Next, air dry with a moisture-free and oil-free air for five seconds.

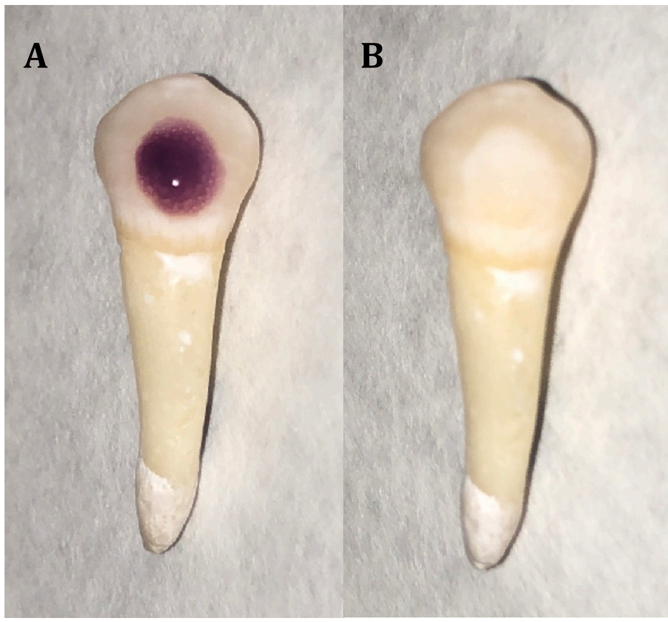


Figure 16. (A) Sample tooth with etch. (B) White, chalky appearance following etching.

Figure 17. Sample tooth with primer

The small wire bonder Mini Mold attachment (Ortho Arch, Schaumburg, IL) was used as the clear aligner attachment template for this study. Unitek Transbond XT composite (3M, St. Paul, MN) was packed firmly into the attachment well until the material is filled up to the top of the well. The attachment template will be seated firmly on the tooth and light-cured for 4 seconds using the VALO Ortho light-emitting diode curing light (Ultradent, South Jordan, UT) (Figures 18, 19, and 20). The manufacturer's instructions were followed and the curing light was held at a distance of 4-5 millimeters from the adhesive. Following the bonding of the attachments, the teeth were again stored in distilled water for one week at 37 °C. Next, the sample teeth were thermocycled (1,000 cycles submerged in water between 5 degrees Celsius and 51 degrees Celsius) for 12 hours (Figure 21). All sample teeth were thermocycled simultaneously and each group was placed in a separate mesh bag to prevent mixing of the samples.

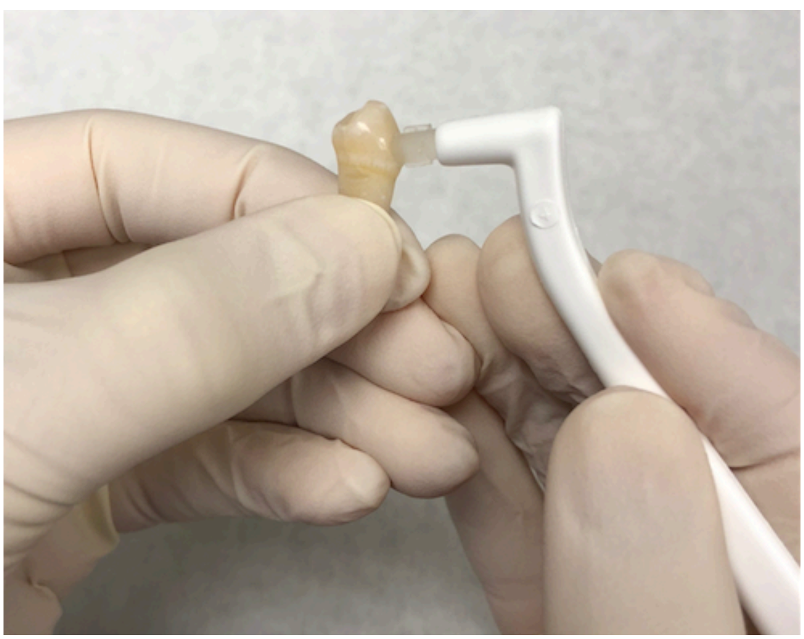


Figure 18. Positioning clear aligner attachment to be bonded

Figure 19. Light-curing of clear aligner attachment

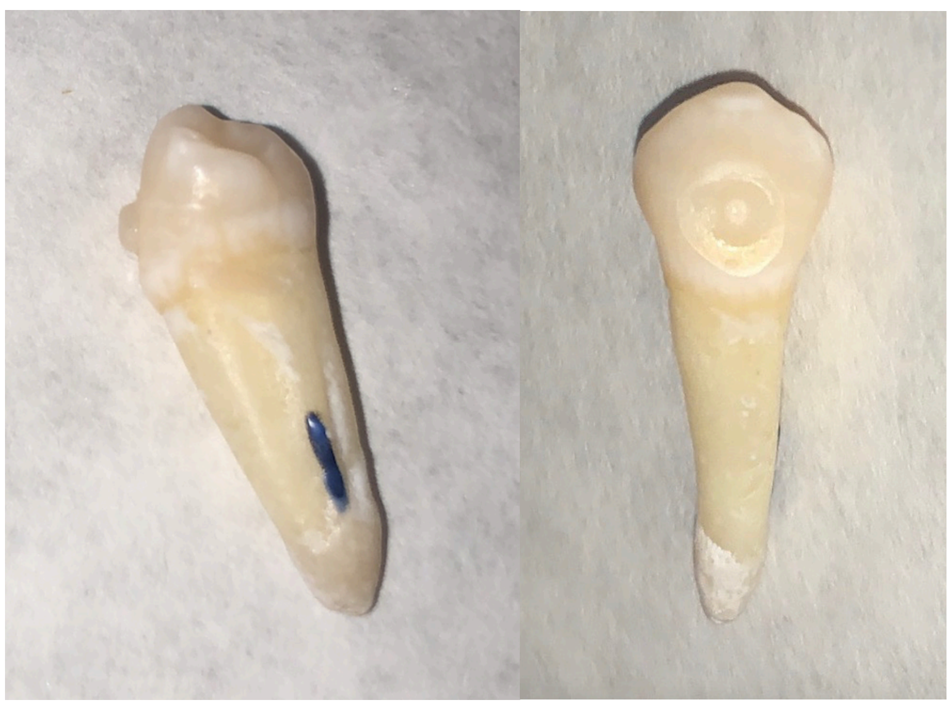


Figure 20. Clear aligner attachment bonded to sample tooth

Figure 21. Thermocycler

2.6 Attachment Removal

Four methods were tested to remove the composite attachments from the buccal surfaces of the experimental teeth according to the protocol of the group in which they were categorized (see figure 1). A Fotona Er:YAG (erbium yttrium-aluminum garnet) laser (Fotona, Dallas, TX) was used in this study (Figure 22). Prior to attachment removal, the sample teeth were mounted in microstone blocks to stabilize the samples (Figure 23). During attachment removal, a K-type microthermocouple (Liumy Tools, ShenZhen, China) was inserted into the access hole of each tooth during attachment removal (Figure 24). A thermocouple controller (Liumy Tools, ShenZhen, China) was used to record the thermal data and the highest temperature measured was recorded during attachment removal. The composite attachments were removed by the designated removal methods until the attachment was completely removed (Figures 25 and 26).

Attachment removal was achieved by a single operator under loupe magnification following the proper safety precautions.

Figure 22. Fotona Er:YAG laser

Figure 23. Sample tooth mounted in microstone block

Figure 24. Liumy Tools K-type thermocouple

Figure 25. High-speed handpiece with multi-fluted tungsten-carbide debonding bur

Figure 26. Attachment removal with Er:YAG laser

2.7 Post-treatment Measurements

After completing attachment removal, the teeth were cleaned with non-fluoridated pumice for 10 seconds, then thoroughly rinsed with a water spray, and air-dried. Post-treatment enamel surface roughness value (Ra) was measured using the Veeco DEKTAK 150 stylus profilometer for all sample teeth. Again, three roughness measurements (Ra) at three different sites were made in μm for each tooth and an average was calculated. In addition, a second stereomicroscopic evaluation was performed using the Olympus SZX7 stereomicroscope (Olympus, Tokyo, Japan) at a magnification of 10X and 25X to evaluate the enamel surface topography. Lastly, a post-treatment enamel surface gloss measurement (degrees) was measured using the Novo-Curve Glossmeter (Rhopoint Instruments, Hastings, UK).

2.8 Statistical Analysis

A power analysis was performed to determine the number of extracted teeth required to perform with study with statistically significant results. We wanted to detect a standardized effect of 0.50 with a power of 80% and an alpha of 0.05; therefore, a sample size of 80, with 20 per group, was needed. However, only forty extracted human premolars that met the investigator's inclusion criteria were collected.

Descriptive statistics were calculated for all study variables. A one-way between ANOVA was conducted to compare the effects of different clear aligner attachment removal methods (carbide bur; Er:YAG laser at 215 mJ/30 Hz/6.45 W; Er:YAG laser at 300 mJ/20 Hz/6 W; Er:YAG at 240 mJ/20 Hz/4.8 W) on surface roughness, surface gloss, and pulpal temperature change. A Tukey HSD post hoc test was used for all post hoc comparisons. RStudio and R 3.2.2 was used for all statistical analysis, and significance is accepted at $p < 0.05$.

2.1 Surface Roughness

Analysis of variance showed an effect of treatment group on roughness, $F(4, 39) = 31.19$, $p < 0.001$, $\eta p2 = 0.76$. Post hoc analyses using the Tukey HSD post hoc criterion for significance indicated that the average roughness score was significantly lower before treatment (M = 0.32, SD = 0.13) than group one (M = 5.45, SD = 1.48, $p < 0.001$), group two (M = 8.69, SD = 1.52, $p < 0.001$) and group three (M = 7.62, SD = 2.34, $p < 0.001$). Post hoc analyses using the Tukey HSD post hoc criterion for significance also indicated that the average roughness score was significantly lower in the control group (M = 2.77, SD = 1.18) than in experimental group 1 (M = 5.45, SD = 1.48, $p < 0.001$), experimental group 2 (M = 8.69, SD = 1.52, $p < 0.001$), and experimental group 3 (M = 7.62, SD = 2.34, $p < 0.001$) — Tables 1 & 2, and Figure 26.

2.2 Surface Gloss

Analysis of variance showed an effect of treatment group on gloss, $F(3, 36) = 15.91$, $p < 0.001$, $\eta p2 = 0.57$. Post hoc analyses using the Tukey HSD post hoc criterion for significance indicated that the average gloss was significantly lower in the control (M = -5.93, SD = 1.67) than experimental group 1 (M = -12.25, SD = 3.39, $p < 0.001$), experimental group 2 (M = -13.36, SD = 3.12, $p < 0.001$) and experimental group 3 (M = -11.89, SD = 2.03, $p = 0.001$). — Tables 1 & 2, and Figure 27.

2.3 Pulp Temperature

Analysis of variance showed an effect of treatment group on temperature, $F(3, 36) = 6.54$, $p = 0.001$, $\eta p2 = 0.35$. Post hoc analyses using the Tukey HSD post hoc criterion for significance indicated that the average temperature was significantly lower in the control group ($M = 1.58$, $SD = 0.53$) and experimental group 2 ($M = 1.49$, $SD = 0.29$) than experimental group 1 ($M = 2.14$, $SD = 0.26$, $p = 0.006$) and experimental group 3 ($M = 2.14$, $SD = 0.26$, $p = 0.001$).—Tables 1 & 2, and Figure 28.

Chapter 4: Discussion

As an orthodontist, the primary goal following orthodontic debonding is to return the enamel surface of the teeth to their pretreatment state by removal of the residual surface composite. With the growing popularity of clear aligners in the field of orthodontics, large composite attachments on a multitude of teeth are necessary to achieve the doctor's dental treatment goals. The aim of this study was to determine if laser can be used as a safe alternative to remove clear aligner attachments with little to no undesired effects to enamel surface and pulp chamber. Undesired effects include increased enamel surface roughness, decreased gloss, and pulpal temperature increase of 5.5 °C.

The results of this investigation showed that regardless of the clear aligner attachment removal method, there was an increased enamel surface roughness. This increased enamel surface roughness was still present after polishing the enamel surfaces with pumice. However, the average roughness score was lower and statistically significant in the control group where the clear aligner attachments were removed with a multi-fluted tungsten-carbide bur compared to the three laser groups. Similarly, these results were congruent with those of *Yassaei et al* who used Er:YAG laser at 125 mJ/20 Hz/ 2.5 W for residual orthodontic adhesive removal[17]. Additionally, *Ahrari et al* found similar results when using Er:YAG laser at 250 mJ/4 Hz to remove composite remnants following orthodontic debonding[41]. In a study by *Fried et al*, it was concluded that Er:YAG lasers with a fluence range of 3-50 J/cm^2 at 100 Hz (30W) can cause some enamel damage, however, there was no loss of superficial enamel in some of the samples[42]. All of the classic studies that have evaluated enamel surface roughness after residual composite debonding have relied heavily on qualitative measures via scanning electron microscopy (SEM) in analyzing their results[5, 9, 10, 17, 43, 44]. Qualitative analysis of enamel surface roughness is subjective and may introduce evaluator bias to favor the original hypotheses. Since scanning electron microscopy isn't able to provide sufficient quantitative data, it is impossible to measure the extent of enamel damage on a continuous scale. With the use of a profilometer, researchers obtain more descriptive data to quantify the severity of enamel damage. Despite this technology, only a couple studies have used as their means for measuring the enamel surface roughness[41, 45]. This lack of quantitative data describing enamel surface roughness in the literature contributed to the decision for using profilometry in this study.

Previous studies[46, 47] have made associations between increased surface roughness and decreased gloss; defined as the angular selectivity of reflectance involving surface-reflected light that quantifies esthetic surface appearance. Decreased gloss presumes that there is a decreased esthetic appearance of the treated surface. To date, no studies have been published investigating the effect of various residual composite (or clear aligner attachment) removal methods on enamel surface glass. Similarly to roughness, the results of this study showed that regardless of the clear aligner attachment removal method, there was a decreased enamel gloss post-treatment. Like the previous studies that associated increased surface roughness with decreased gloss, this study also showed this negative correlation. The decrease in enamel gloss was lowest and statistically significant in the control group when compared to the experimental groups.

There was a decrease in gloss in all groups according to the glossmeter measurements; however, there is no information in the literature describing what decreased magnitude of gloss is clinically relevant.

The effects of all of the clear aligner attachment removal methods were assessed using stereomicroscopy at a magnification of 10X and 25X. In 1979, *Zachrisson and Arthun*[48] evaluated the enamel surface following bracket debonding with the use of stereomicroscopy. They developed their index surface system (0 = perfect surface, 1 = satisfactory, 2 = surface acceptable, 3 = imperfect surface, 4 = unacceptable surface) to describe their findings. However, *Zachrisson's* system is very vague and doesn't describe the quality of the enamel damage. In this study, the multi-fluted tungsten-carbide debonding bur visually provided the smoothest appearing enamel surface (Figure 27), which coincides with the finding that this method yielded the lowest enamel surface roughness. The multi-fluted tungsten-carbide debonding bur appeared to create superficial scratches with few deeper scratches. In experimental laser group 1 (215mJ/30Hz/6.45W) (Figure 28), you begin to visualize circular, opaque streaks that mimic the shape of the laser output beam. The majority of these circular streaks are superficial, however, there is an area that appears to have deeper enamel damage. In experimental laser group 2 (300mJ/20Hz/6W) (Figure 29), extensive circular, opaque streaks can be seen across the entire enamel surface. The shape of the laser output beam is clearly seen and many of these circular lesions are deep. This damaged morphology coincides with the result that this group yielded the largest enamel surface roughness. In experimental laser group 3 (240mJ/20Hz/4.8W) (Figure 30), a similar damage pattern to experimental laser group 3 can be seen; however, the damage is less severe in this group. The fact that experimental laser group 3 had less energy output with the same frequency as experimental laser group 2 explains this finding.

Although pulp temperature rises during clear aligner attachment removal were significantly lower in the control group, all test groups had pulp chamber temperature rises well below the 5.5 ºC limit[33] that *Zach and Cohen* illustrated. Previous studies[7, 38, 39, 40] that evaluated the use of laser and other debonding method on pulp temperature found similar results where the temperature rises were all in a safe range. Unless an extremely large Er:YAG energy output is used to remove residual adhesive or clear aligner attachments, there is a low risk of pulpal necrosis.

Limitations of this study include that only forty extracted human premolars that met the inclusion criteria for tooth selection. Power analysis determined that eighty extracted teeth were required to perform with study with statistically significant results; however, only forty extracted human premolars that met the investigator's inclusion criteria were collected. Since the sample size was small, there was a limit to how many laser settings could be tested for clear aligner attachment removal. Lastly, the profilometer used in this study was unable to measure the surface roughness of the extracted premolars because the convexity of the teeth was so great. This lead to the erosion of the facial surfaces of the teeth so that the profilometer could be used to measure surface roughness. However, an enamel polishing study by *Mullan et al* concluded that eroded enamel was representative of intact enamel[49].

Future studies should focus on testing more laser settings with different combinations of energy output (mJ) and frequency (W). Efforts should also focus on laser selectivity of composite or the development of composites that are easily ablated by laser without damaging the underlying enamel surface. In addition, future studies should focus on the sub-superficial layers of enamel irradiated with laser to determine if the superficial and sub-superficial laser can undergo any remineralization.

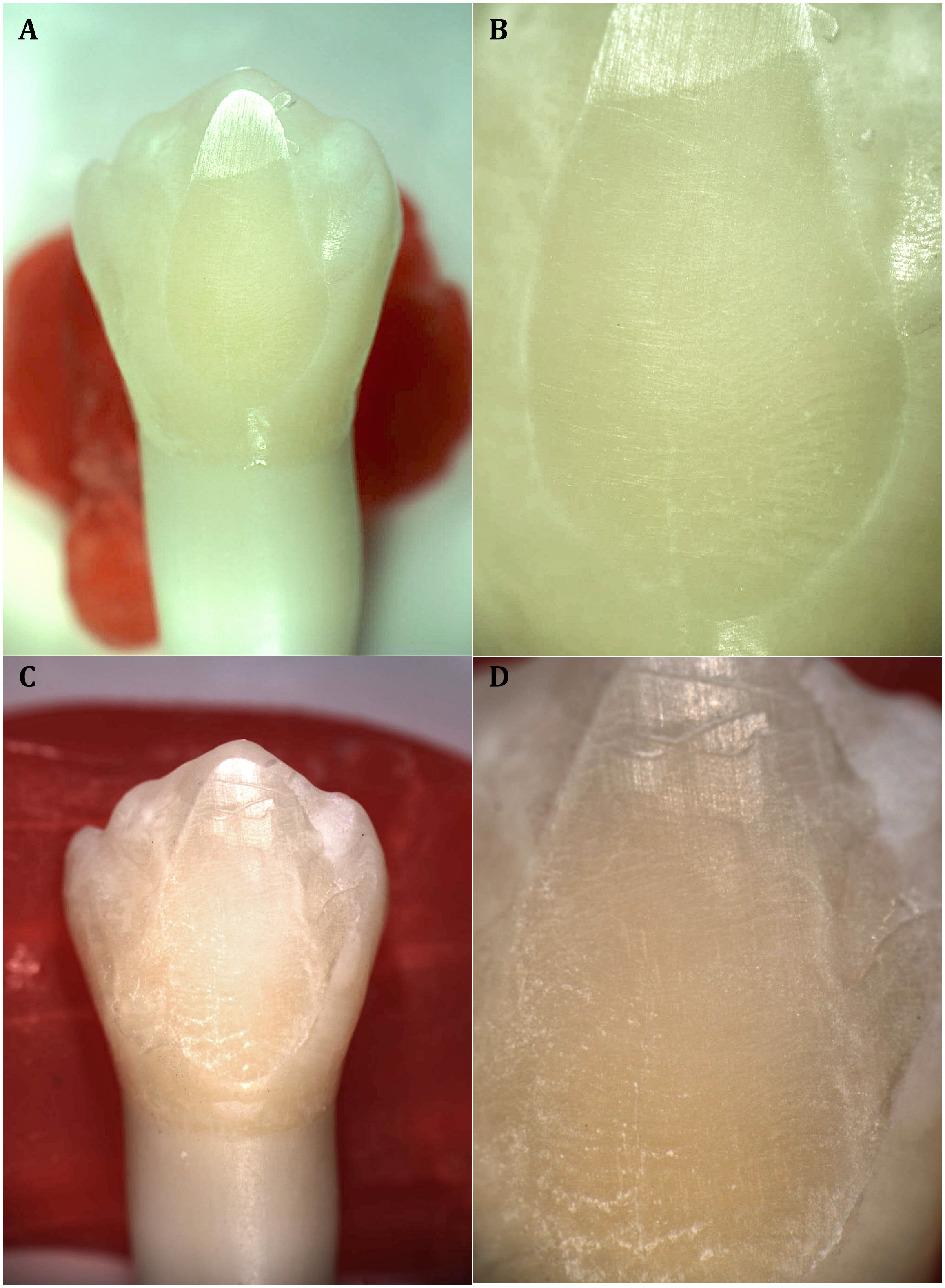


Figure 27. Control group (A) Before 10X (B) Before 25X (C) After 10X (D) After 25X

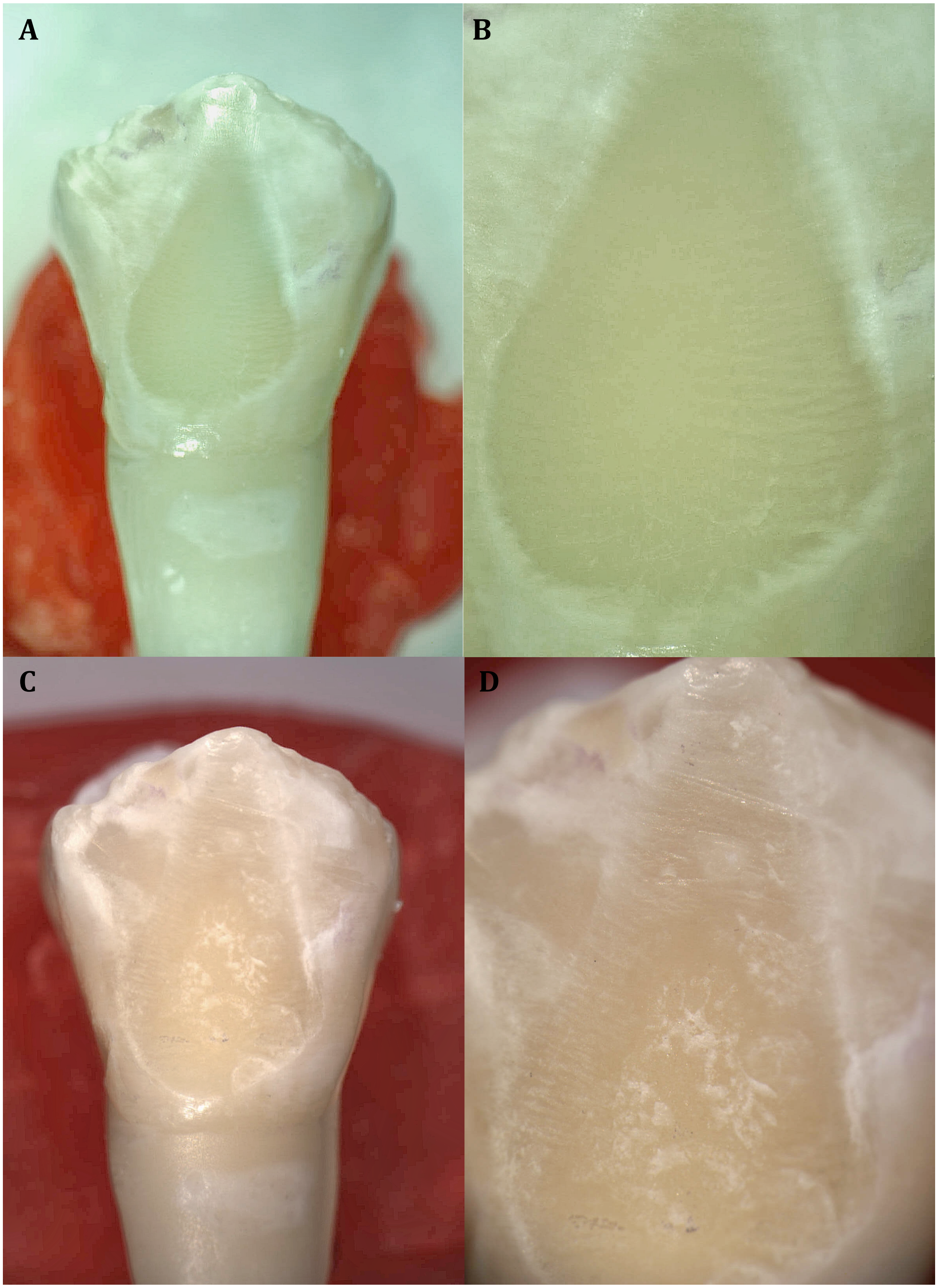


Figure 28. Exp. Group 1 (A) Before 10X (B) Before 25X (C) After 10X (D) After 25X

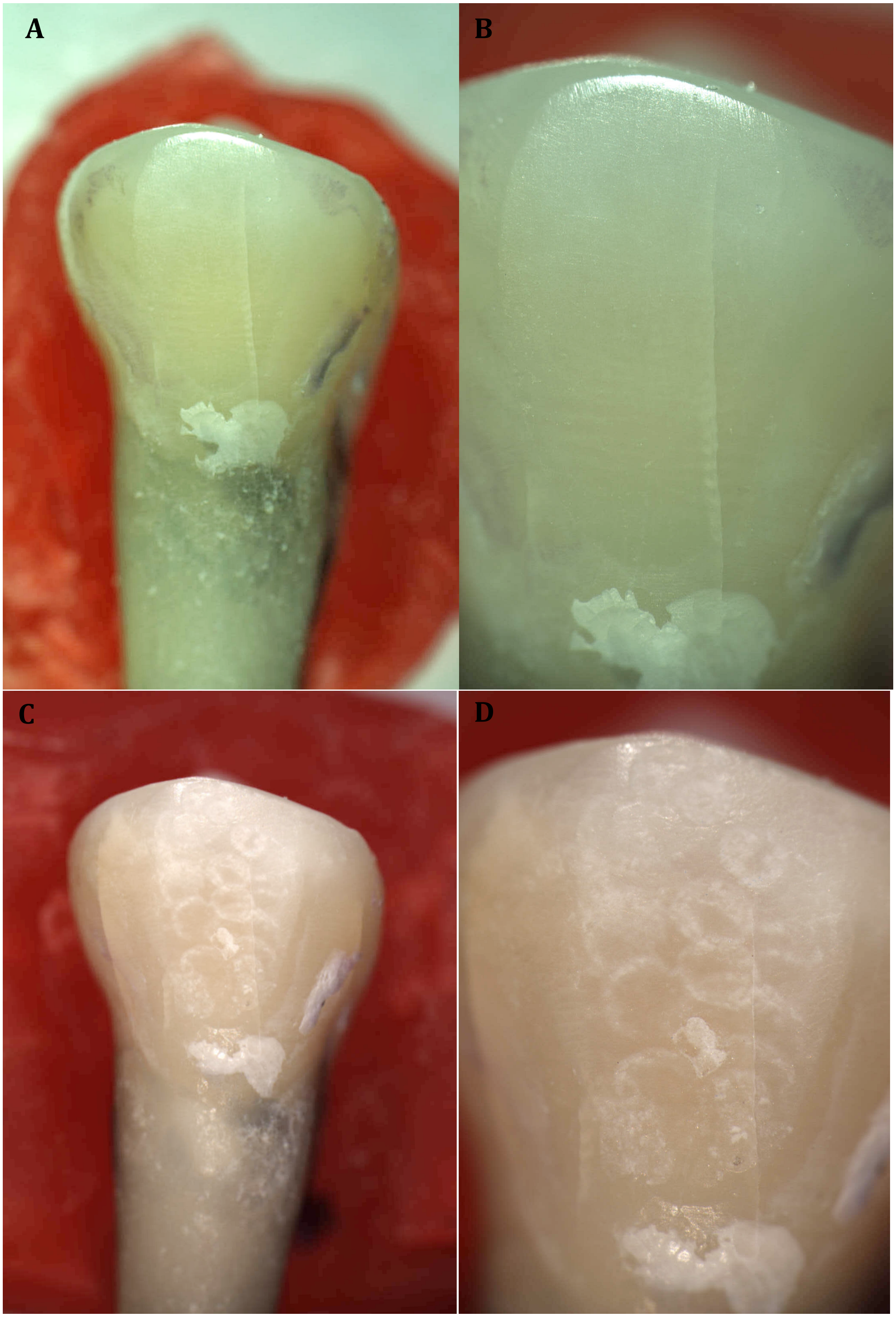


Figure 29. Exp. Group 2 (A) Before 10X (B) Before 25X (C) After 10X (D) After 25X

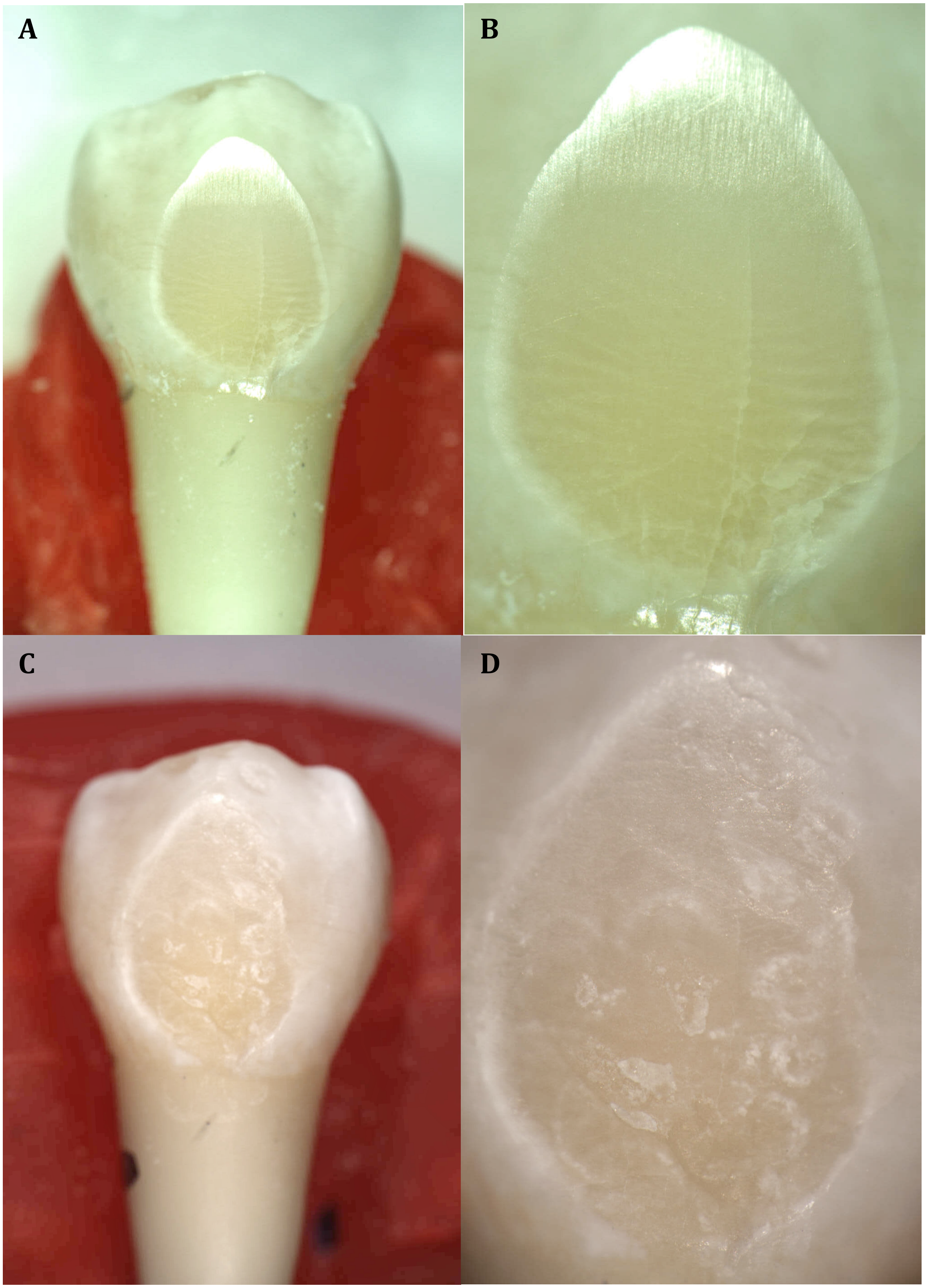


Figure 30. Exp. Group 3 (A) Before 10X (B) Before 25X (C) After 10X (D) After 25X

Chapter 5: Conclusions

Based on this study, the following recommendations and conclusions can be made regarding the removal of composite clear aligner attachments:

1. All four clear aligner attachment removal methods significantly increased the enamel surface roughness; however, profilometry confirmed that the multi-fluted tungsten-carbide bur caused the least amount of surface roughness to the enamel surface.
2. All four clear aligner attachment removal methods significantly decreased the gloss of the enamel surface; however, the multi-fluted tungsten-carbide bur provided the lowest decrease.
3. All four clear aligner attachment removal methods visually damaged the enamel surface; however, the multi-fluted tungsten-carbide bur provided the least visual enamel damage.
4. The multi-fluted tungsten-carbide bur and Er:YAG laser can remove clear aligner attachments with very little to no risk of pulpal necrosis.

Appendices – Raw Data

Appendix A - Pre-treatment Enamel Surface Roughness

GROUP	Ra (mm) - After 1	Ra (mm) - After 2	Ra (mm) - After 3	Ra (mm) - After Avg
Control	0.15462	0.15275	0.12941	0.145593333
Exp. Group 1	0.27168	0.33439	0.30862	0.304896667
Exp. Group 2	0.38455	0.50667	0.43915	0.443456667
Exp. Group 3	0.41928	0.369	0.35103	0.37977

Appendix B - Post-treatment Enamel Surface Roughness

GROUP	TOOTH #	Ra (μm) - After 1	Ra (mm) - After 2	Ra (mm) - After 3	Ra (mm) - After Avg
Control	1	1.66177	2.64415	1.3475	1.884473333
Control	2	1.94773	1.58208	2.05925	1.86302
Control	3	2.78744	2.04161	2.20887	2.345973333
Control	4	1.4997	1.25771	1.57195	1.44312
Control	5	4.45457	4.23673	3.92234	4.204546667
Control	6	2.9199	2.41915	2.51294	2.61733
Control	7	5.23087	3.65202	4.70853	4.530473333
Control	8	5.15345	4.46805	3.70725	4.442916667
Control	9	1.96112	1.45627	2.06305	1.826813333
Control	10	2.56902	2.09909	2.99958	2.555896667
Exp. Group 1	1	4.28294	5.66308	4.53711	4.82771
Exp. Group 1	2	6.27996	4.67062	6.3976	5.782726667
Exp. Group 1	3	2.73174	7.29891	2.40465	4.1451
Exp. Group 1	4	5.35461	6.50035	5.97755	5.94417
Exp. Group 1	5	6.84589	5.84993	6.86631	6.52071
Exp. Group 1	6	5.52966	1.47097	4.32125	3.77396
Exp. Group 1	7	2.90485	2.35408	3.76438	3.00777
Exp. Group 1	8	5.47512	6.94399	5.2269	5.882003333
Exp. Group 1	9	6.09766	8.34102	6.25112	6.8966
Exp. Group 1	10	9.07837	6.94922	7.11609	7.71456
Exp. Group 2	1	11.57706	11.56049	5.24381	9.460453333
Exp. Group 2	2	12.2781	7.04868	9.49696	9.607913333
Exp. Group 2	3	10.41946	10.15137	5.45008	8.673636667
Exp. Group 2	4	5.68292	6.41718	3.20487	5.101656667
Exp. Group 2	5	12.25372	7.79793	9.49688	9.84951
Exp. Group 2	6	9.93197	8.84773	11.5579	10.11253333
Exp. Group 2	7	6.15169	9.97912	9.44231	8.524373333
Exp. Group 2	8	7.21699	9.12698	10.61344	8.985803333
Exp. Group 2	9	10.70467	5.76527	4.91465	7.128196667
Exp. Group 2	10	11.83444	6.63861	9.94538	9.47281
Exp. Group 3	1	9.40737	3.07581	6.39133	6.291503333
Exp. Group 3	2	9.71302	9.08174	7.11422	8.636326667
Exp. Group 3	3	4.20972	6.27967	5.97997	5.489786667
Exp. Group 3	4	8.30692	10.44899	10.52649	9.7608
Exp. Group 3	5	2.4905	2.8584	3.26835	2.872416667
Exp. Group 3	6	7.40014	6.09412	6.89349	6.795916667
Exp. Group 3	7	5.44093	6.35648	9.38834	7.061916667
Exp. Group 3	8	8.95249	9.47193	10.5578	9.66074
Exp. Group 3	9	9.88964	10.92844	7.61004	9.47604
Exp. Group 3	10	12.12839	8.52948	9.78752	10.14846333

Appendix C - Enamel Surface Gloss (Pre- and Post-treatment)

GROUP	TOOTH #	Gloss (degrees) - Before	Gloss (degrees) - After	Δ in Gloss (degrees)
Control	1	22	19.6	-2.4
Control	2	23.5	18.2	-5.3
Control	3	18	13.6	-4.4
Control	4	57.2	48.5	-8.7
Control	5	42.1	35.7	-6.4
Control	6	45.4	38.5	-6.9
Control	7	29.5	23.3	-6.2
Control	8	22.3	16.3	-6
Control	9	32.4	25.5	-6.9
Control	10	36.6	30.5	-6.1
Exp. Group 1	1	56.2	42.7	-13.5
Exp. Group 1	2	41.4	23.2	-18.2
Exp. Group 1	3	41.9	33.5	-8.4
Exp. Group 1	4	43.2	28.4	-14.8
Exp. Group 1	5	36.1	21.2	-14.9
Exp. Group 1	6	38.4	29.4	-9
Exp. Group 1	7	29	20.3	-8.7
Exp. Group 1	8	29.9	15.8	-14.1
Exp. Group 1	9	26.3	17.4	-8.9
Exp. Group 1	10	37.8	25.8	-12
Exp. Group 2	1	28.7	13.1	-15.6
Exp. Group 2	2	25.7	13	-12.7
Exp. Group 2	3	25.9	12.8	-13.1
Exp. Group 2	4	27.8	16.6	-11.2
Exp. Group 2	5	30.7	18.9	-11.8
Exp. Group 2	6	43.4	24.6	-18.8
Exp. Group 2	7	15.1	8.1	-7
Exp. Group 2	8	38.4	23	-15.4
Exp. Group 2	9	41.5	27.6	-13.9
Exp. Group 2	10	35	20.9	-14.1
Exp. Group 3	1	23	14.7	-8.3
Exp. Group 3	2	26	13.2	-12.8
Exp. Group 3	3	33.6	23.3	-10.3
Exp. Group 3	4	27.9	14.5	-13.4
Exp. Group 3	5	43.7	33.6	-10.1
Exp. Group 3	6	30.8	20.4	-10.4
Exp. Group 3	7	28.6	13.9	-14.7
Exp. Group 3	8	24.6	11.2	-13.4
Exp. Group 3	9	23.9	12	-11.9
Exp. Group 3	10	23.8	10.2	-13.6

Appendix D - Pulpal Temperature Change During Attachment Removal

GROUP	TOOTH #	Δ in Pulp Temp (degrees C)
Control	1	1.8
Control	2	0.9
Control	3	1.4
Control	4	2.4
Control	5	1.8
Control	6	2.1
Control	7	1.9
Control	8	1.6
Control	9	1.2
Control	10	0.7
Exp. Group 1	1	2.1
Exp. Group 1	2	1.7
Exp. Group 1	3	1.4
Exp. Group 1	4	1.9
Exp. Group 1	5	2.2
Exp. Group 1	6	2
Exp. Group 1	7	1.5
Exp. Group 1	8	1.6
Exp. Group 1	9	1.6
Exp. Group 1	10	2.2
Exp. Group 2	1	1.5
Exp. Group 2	2	1.3
Exp. Group 2	3	1
Exp. Group 2	4	1.4
Exp. Group 2	5	1.9
Exp. Group 2	6	1.7
Exp. Group 2	7	1.5
Exp. Group 2	8	1.6
Exp. Group 2	9	1.2
Exp. Group 2	10	1.8
Exp. Group 3	1	2.2
Exp. Group 3	2	2.1
Exp. Group 3	3	1.8
Exp. Group 3	4	2
Exp. Group 3	5	2.4
Exp. Group 3	6	2.2
Exp. Group 3	7	2.1
Exp. Group 3	8	2.7
Exp. Group 3	9	1.9
Exp. Group 3	10	2

Table 1. Descriptive Statistics for Study Variables

	Group	N	Mean	SD	Min	Max
Surface Roughness	Before	4	0.32	0.13	0.15	0.44
	Control	10	2.77	1.18	1.44	4.53
	Group 1	10	5.45	1.48	3.01	7.71
	Group 2	10	8.69	1.52	5.10	10.11
	Group 3	10	7.62	2.34	2.87	10.15
Gloss	Control	10	-5.93	1.67	-8.70	-2.40
	Group 1	10	-12.25	3.39	-18.20	-8.40
	Group 2	10	-13.36	3.12	-18.80	-7.00
	Group 3	10	-11.89	2.03	-14.70	-8.30
Pulp Temperature	Control	10	1.58	0.53	0.70	2.40
	Group 1	10	1.82	0.30	1.40	2.20
	Group 2	10	1.49	0.28	1.00	1.90
	Group 3	10	2.14	0.26	1.80	2.70

Table 2. ANOVA Tables for Study Design

			Ra (mm)		
	SS	Df	F-Value	Pr (>F)	pes
(Intercept)	0.41	1	0.15	0.697	0.00
Group	328.18	4	31.19	0.000	0.76
Residuals	102.58	39			
			Gloss		
	SS	Df	F-Value	Pr (>F)	pes
(Intercept)	351.65	1	50.04	0.000	0.582
Group	335.48	3	15.91	0.000	0.570
Residuals	252.98	36			
			Temperature		
	SS	Df	F-Value	Pr (>F)	pes
(Intercept)	24.96	1	193.48	0.000	0.84
Group	2.53	3	6.54	0.001	0.35
Residuals	4.65	36			

Table 3. Pairwise Comparisons Using a Tukey HSD Test

Ra (mm)	Difference	Lower 95% CI	Upper 95% CI	p-value
Before - Control	-2.45	-4.33	-0.57	0.099
Before - Group 1	-5.13	-7.01	-3.25	<.0001
Before - Group 2	-8.37	-10.25	-6.49	<.0001
Before - Group 3	-7.30	-9.18	-5.42	<.0001
Control - Group 1	-2.68	-4.11	-1.25	0.006
Control - Group 2	-5.92	-7.35	-4.49	<.0001
Control - Group 3	-4.85	-6.28	-3.42	<.0001
Group 1 - Group 2	-3.24	-4.67	-1.81	0.001
Group 1 - Group 3	-2.17	-3.60	-0.74	0.036
Group 2 - Group 3	1.07	-0.36	2.50	0.582
Gloss	**Difference**	**Lower 95% CI**	**Upper 95% CI**	**p-value**
Control - Group 1	6.32	3.99	8.65	<.0001
Control - Group 2	7.43	5.10	9.76	<.0001
Control - Group 3	5.96	3.63	8.29	0.000
Group 1 - Group 2	1.11	-1.22	3.44	0.786
Group 1 - Group 3	-0.36	-2.69	1.97	0.990
Group 2 - Group 3	-1.47	-3.80	0.86	0.606
Temperature	**Difference**	**Lower 95% CI**	**Upper 95% CI**	**p-value**
Control - Group 1	-0.24	-0.55	0.07	0.452
Control - Group 2	0.09	-0.22	0.40	0.943
Control - Group 3	-0.56	-0.87	-0.25	0.007
Group 1 - Group 2	0.33	0.02	0.64	0.188
Group 1 - Group 3	-0.32	-0.63	-0.01	0.210
Group 2 - Group 3	-0.65	-0.96	-0.34	0.001

Figure 31. Mean plot with 95% standard error bars for surface roughness

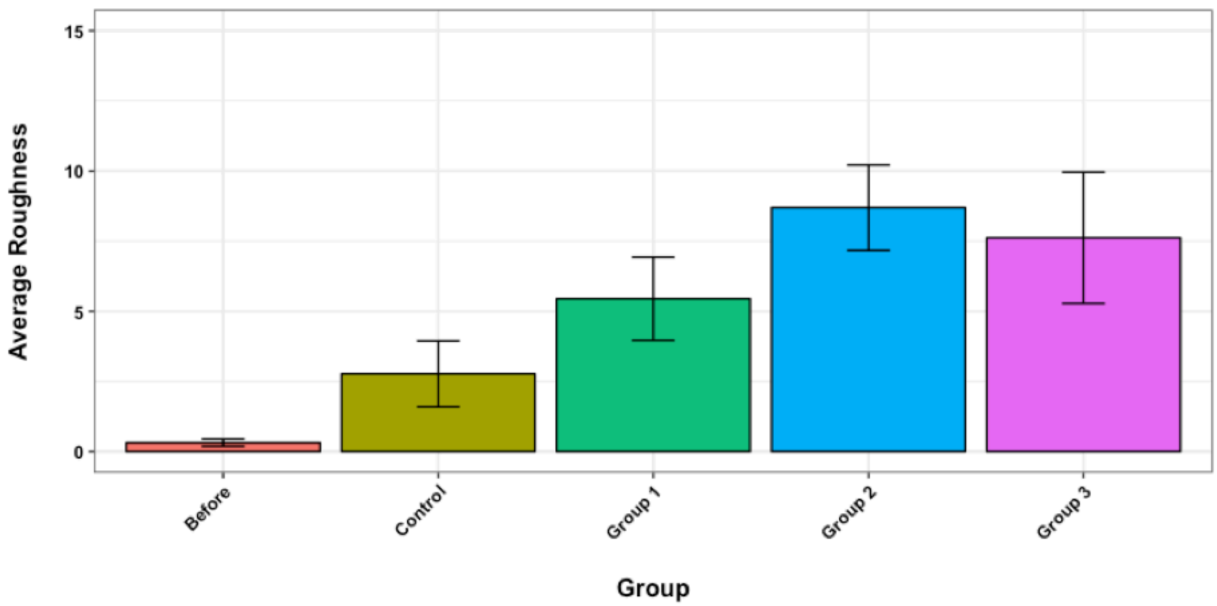


Figure 32. Mean plot with 95% standard error bars for gloss

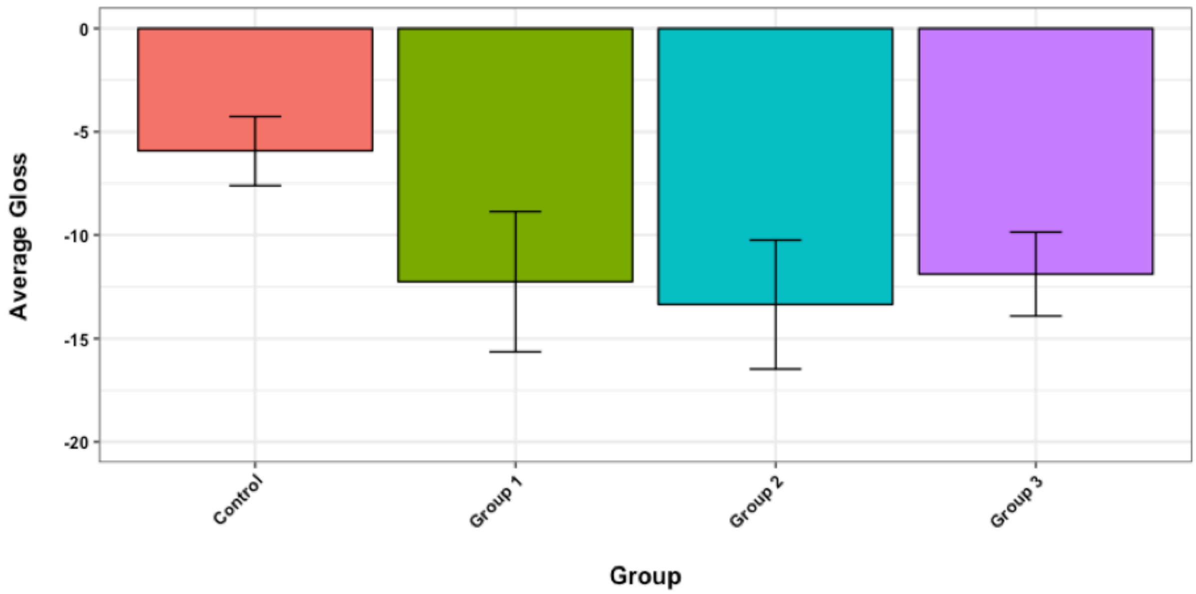
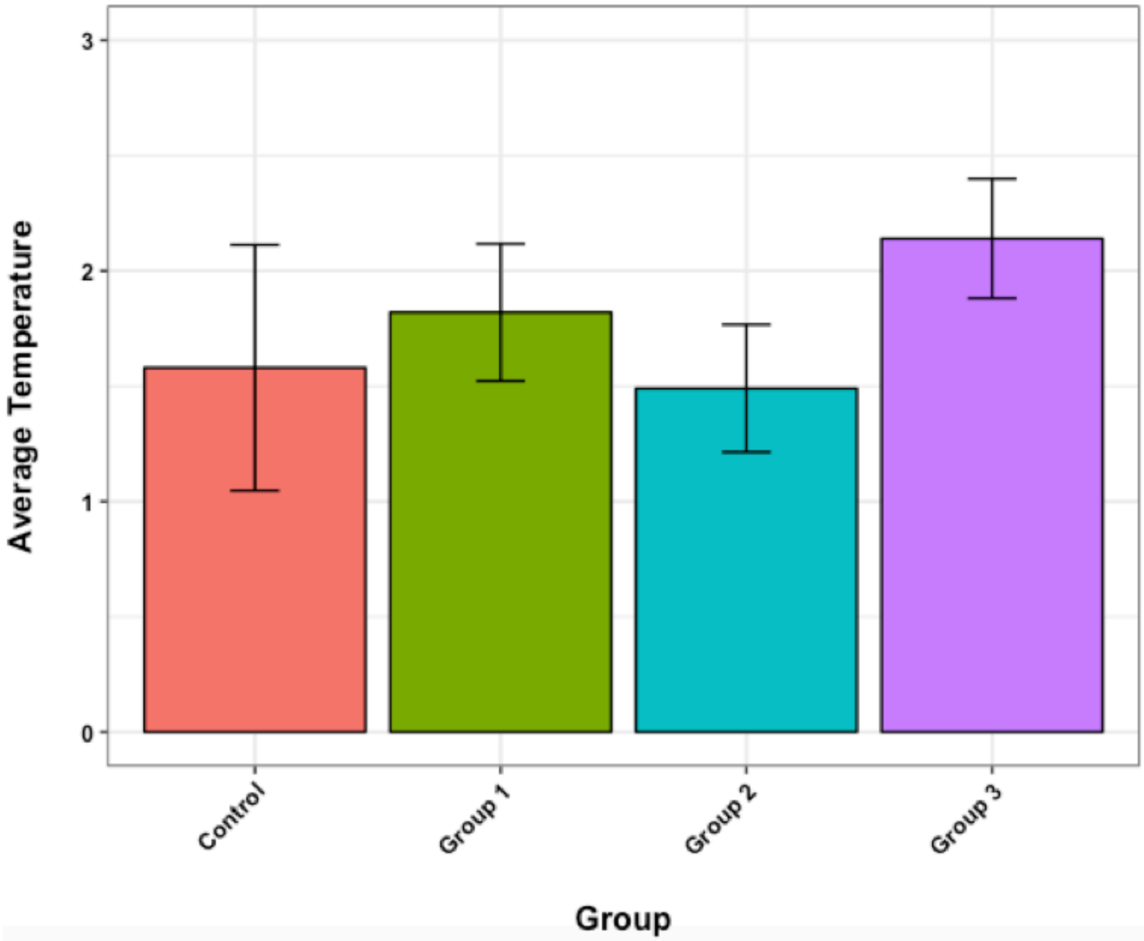


Figure 33. Mean plot with 95% standard error plots for temperature



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