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Effect of Air-abrasion Preparation on Shear Bond Strength of Orthodontic Brackets to Enamel Surface

Elliott Katz

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THE EFFECT OF AIR-ABRASION PREPARATION ON SHEAR BOND STRENGTH
OF ORTHODONTIC BRACKETS TO ENAMEL SURFACE

ELLIOTT N. KATZ, D.D.S.

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

December 2018

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By

ELLIOTT N. KATZ, D.D.S.

A Thesis Submitted to the College of Dental Medicine of Nova Southeastern

University in Partial Fulfillment of the Requirements for the Degree of

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Department of Orthodontics and Dentofacial Orthopedics

College of Dental Medicine

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December 2018

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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.D. degree and for this assignment.

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_____ Date

DEDICATION

This thesis is dedicated to my friends and family who have helped me throughout my life and every level of my education. Without them, I wouldn't be where I am today. A special dedication to my late grandparents, the Honorable David and Joan Katz, and Dr. Jerome and Rhona Weinstein who were taken from us far too early. They taught me the values of kindness, compassion, empathy, family, honor, and professionalism. Their unwavering love and fierce support will be with me always.

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ABSTRACT

THE EFFECT OF AIR-ABRASION PREPARATION ON SHEAR BOND STRENGTH OF ORTHODONTIC BRACKETS TO ENAMEL SURFACE

DEGREE DATE: December 2018

ELLIOTT N. KATZ, D.D.S.

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Introduction: An optimal orthodontic bonding system must minimize damage to the enamel during conditioning, have enough bond strength to prevent bracket de-bonding during treatment, and allow bracket removal at treatment completion, such that minimal damage is inflicted to the tooth.¹ Pumice followed by acid etching has been the standard for many years; however, Groman Inc. (Margate, FL, USA) has stated that using their air-abrasion product will result in a tripling of bond strength. This method claims a three-fold increase in bond strength compared to traditional acid etching techniques by substituting air-abrasion using the EtchMaster® (Groman Inc., Margate, FL) 50 µm aluminum oxide in place of pumice prophylaxis prior to acid etching. The purpose of this study is to see if this combination does in fact triple shear bond strength, and if so, what impact it has on the residual enamel surface after bracket removal, or de-bonding.

Methods: Ninety recently extracted bovine incisors were randomly divided into three groups. Each of the three groups underwent different conditioning methods prior to bracket bonding. Group A: pumice + acid etch (N=30), Group B: air-abrasion + acid etch (N=30), and Group C: air-abrasion only (N=30). Enamel surface conditions were characterized using a Quanta 200 Scanning Electron Microscope (SEM) (FEI, Hillsboro, OR) and a SZX7 Stereomicroscope System (Olympus, Center Valley, PA). American Orthodontics Master Series System twin MBT mandibular incisor brackets (Sheboygan, WI, USA) were then bonded to each tooth. Following bonding, teeth were stored for twenty-four hours in water at 37°C +/- 2°C. All groups then underwent thermocycling of five hundred cycles in water baths set at five and fifty-five degrees Celsius. Next, the samples were mounted in dental stone and brackets de-bonded using a universal testing machine (Instron, Canton, MA) to obtain shear bond strength (SBS) values. SEM and optical stereomicroscopy were again utilized to evaluate the enamel surface and determine the adhesive remnant index (ARI) was score of each specimen.

Results: The mean of Group A (pumice + acid etch) was 21.52 MPa with a standard deviation of 4.97 MPa. The mean of Group B (air-abrasion + acid etch) was 21.83 MPa with a standard deviation of 7.55 Mpa. The mean of Group C (air-abrasion only) was 8.12 MPa with a standard deviation of 3.05 MPa. Analysis of variance showed a main effect of Group on MPa, $F(2, 87) = 60.66$, $p < 0.001$, $\eta^2 = 0.58$. Post-hoc analyses using Tukey's HSD indicated that SBS values were higher for teeth in Group A than for those in Group C ($p < 0.001$), teeth in Group B had higher SBS values than those in Group C ($p < 0.001$), but no difference was found for SBS between teeth in Group A and Group B ($p = 0.981$). Results from the Fisher's Exact test, where we controlled the Type I error using

a Bonferroni correction, reveals that ARI scores differed by group ($p < 0.001$). Stereomicroscope images at 38.75x magnification obtained following enamel conditioning show Groups A (P+AE) and B (AA+AE) are almost indistinguishable; however, Group C (AA) has visual differences. Group C had a speckled reflective property that appeared to be residual aluminum oxide particles. Following de-bond, stereomicroscopic and SEM images showed no enamel defects on the tooth.

Conclusions: SBS was not significantly different between Group A (pumice + acid etch) and Group B (air-abrasion + acid etch). SBS was significantly different between Groups A and B, and Group C (air-abrasion only). This means there is not a three-fold increase in SBS when using air-abrasion and acid etch, when compared to pumice and acid etch, as claimed by the manufacturer of the air-abrasion unit used in this study. Additionally, the air-abrasion only group displayed a significantly lower SBS than Group A and B. Air-abrasion only is not a suitable enamel preparation method for orthodontic bonding. Images obtained from the stereomicroscope and SEM reveal no observational damage to the enamel surface topography after de-bonding for any group.

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Chapter 1: Introduction

1.1 Background on Orthodontic Bonding Techniques

Orthodontic treatment in the early 1900s was achieved by fitting a metal band around each tooth. In 1955, Buonocore² utilized 85% phosphoric acid to increase acrylic resin adhesion on enamel. In 1965, the first directly bonded orthodontic metal brackets were introduced by Newman.³ These combined an epoxy adhesive and an acid etch technique to bond to enamel. The purpose of the acid etch treatment is to increase the surface area available for bonding. This in turn alters the enamel from a hydrophobic, or low-energy surface, to a hydrophilic, or high-energy surface.⁴ This approach has been improved over the years with better acid etch methods, better composites, and is now the current standard technique to bond brackets directly to teeth.

Advantages of direct bonding as opposed to banding include better esthetics, no loss of arch perimeter, reduced gingival irritation and better caries control due to better interproximal enamel access, that allows patients to facilitate cleaning between their teeth.⁵ With direct bonding comes the potential for bond failure. Bond failure occurs for many reasons which may include: operator technique, the natural enamel surface topography, the type of adhesive/ bracket systems used and the masticatory forces found in different areas of the oral cavity.⁶ These bond failures create anxiety for both patients and orthodontists because resulting appliance issues need to be repaired. This can lead to extended total treatment time, emergency appointments, and undesired tooth movement.

1.2 History of Air-Abrasion

As with all materials and techniques in dentistry, new ideas and formulations are invented to improve upon the old. One such advent was the concept of air-abrasion. Air-abrasion produces a high-speed stream of abrasive particles, such as aluminum oxide, propelled by air pressure.^{7,8} First implemented in dentistry in the 1940s for restorative purposes, it was seen to have several advantages over traditional belt-driven handpieces for tooth preparation.^{9,10,11} Air-abrasion eliminated pressure on teeth, vibration, and bone conducted noise. It did not generate heat, and reports showed greater patient comfort.⁷ By the late 1950s, air-abrasion had lost popularity due to an inability to create proper GV Black preparation designs,^{12,13,14,15} and the invention of the high-speed air driven handpiece.⁷

Several years later, air-abrasion was revisited, this time in the orthodontic community as an alternative to acid etching in bonding protocols. Research has shown that air-abrasion results in surface changes to enamel, so it was tested to see if it would serve as a sufficient replacement to acid etching.¹⁶ The 1997 study by Olsen et al.¹⁷ at the University of Iowa directly compared the shear bond strength and enamel surface structure created by acid etching versus air-abrasion. Their study utilized three groups with the acid etch group being the control, and two air-abrasion groups of different size particles, 50 μm and 90 μm at 160 psi for 3 seconds at a distance of 10 mm. Shear bond strength, bond failure location, and enamel surface morphology were analyzed for all groups. The conclusion was a statistically significant decrease in bond strength in the air-abraded groups. No composite remained on the tooth at the site of bond failure for the

air-abraded group. The study concluded that air-abrasion alone was not clinically acceptable as an enamel conditioner prior to bracket bonding.

Another study conducted in 1997 by Reisner et al.¹⁸ at the University of Pennsylvania also looked at air-abrasion versus acid etching. This study was two-fold; the first closely examined the enamel surface using profilometry and scanning electron microscopy, and the second part compared de-bonding forces. Four groups were tested:

- A) Air-abrasion only (65-70 psi for 2-3 seconds using 50 µm aluminum oxide at a distance of 6 mm)
- B) Air-abrasion + acid etch (same methods as above)
- C) Abrasion with bur + acid etch
- D) Pumice + acid etch

The results showed no statistically significant difference in surface roughness amongst the groups. This meant air-abrasion was not more damaging to the enamel surface than acid etching as was previously thought. In regard to bond strength, the only group that was significantly different was Group A, which received air-abrasion alone. Group B was found to have the greatest de-bonding force, although differences were not statistically significant. The study concluded that air-abrasion could be used as a polishing substitute, but that it should be followed by acid etching for proper enamel conditioning. The authors also indicated further testing was needed using varying times, pressures, and particle sizes.

A study by Hogervorst et al.¹ in 2000 was very similar to the above studies in its aims. The investigators used a 50 µm aluminum oxide at varying pressures, at a distance of 1 mm for either 15 or 30 seconds. Their conclusions regarding enamel surface

characteristics after treatment were to be expected; increased exposure and or pressure resulted in a higher amount of enamel lost. The bond strength results were consistent with the previous studies as well. The air-abraded groups had significantly lower bond strengths and the study concluded that air abrasion alone is not suitable for enamel conditioning.

To date, there are few studies, and therefore limited data, that have evaluated the efficacy of air-abrasion for orthodontic bonding to enamel. The current literature documents studies that used air-abrasion as a conditioning substitute, not an adjunct to acid etching. The proposed study will investigate the effect on bond strength and the resulting enamel surface morphology under a specific preparation sequence not previously tested.

1.3 Thermocycling

In vitro studies often utilize thermocycling in an attempt to recreate the oral environment. Thermocycling is believed to simulate the rapid changes in temperature extremes noted in the oral cavity and provide a more realistic environment.¹⁹ Some studies show that thermocycling decrease SBS.²⁰ However, other studies show that SBS is stable across all thermal cycles.²¹ There are two main theories as to why thermocycling may affect SBS. The first is that the enamel, the adhesive, and the bracket all have different coefficients of thermal expansion. This means that alternating between extreme temperatures may weaken the bond between these three different components²². The second theory is that thermocycled composites absorb more water than non-

thermocycled composites. This can result in hygroscopic expansion and hydrolytic degradation of the materials.^{22,23}

1.4 Bovine Teeth

The use of bovine teeth in bonding studies is becoming more common due to the similarities with mammalian teeth and difficulties to obtain extracted non-carious human teeth.^{24,25} Mammalian teeth appear quite similar on a histochemical and anatomic basis but are not identical.^{24,25} Yassen et al.²⁶ concluded from their review of the literature that any differences between human and bovine teeth in chemical composition and mineral composition were minor. Moreover, human and bovine teeth reacted similarly during demineralization and remineralization processes.

However, there are differences between the bovine and human teeth that must be taken into account. Bovine enamel and dentin develop quicker than human enamel and dentin. This leads to larger crystal grains and more lattice defects as compared to human enamel.²⁷ Some believe that these differences lead to a lower critical surface tension, which in turn may be a reason why lower SBS values are seen in bovine enamel compared to human enamel.²⁷ Bovine enamel has been shown in various studies to have lower shear bond strength than human enamel. Oesterle et al.²⁴ found bond strength to bovine enamel was 21% to 44% lower than that to human enamel. Additionally, they found that use of deciduous bovine enamel resulted in higher bond strengths compared to permanent bovine enamel, meaning that the two are not interchangeable. An article by Barkmeir and Erickson²⁸ reinforced the notion that bovine enamel is weaker by showing that bovine enamel bond strength was 35% below that of human enamel. All of these are factors that should be accounted for when SBS results are interpreted.

1.5 Shear Bond Strength

One might assume that higher shear bond strength (SBS) is always the goal. This belief however, is incorrect as SBSs that are too high can facilitate practical problems as well. A bonded bracket must withstand forces generated during orthodontic treatment and those transferred to the teeth during mastication and occlusion.²⁹ A systematic review of enamel prepared with 37% phosphoric acid reveals a shear bond strength ranging from 15.2–15.9 megapascals.³⁰ When the SBS is too high, problems can include patient discomfort during bracket de-bonding, bracket damage, or even enamel damage such as enamel flaking, enamel cracks, and tooth fracture.³¹ Studies comparing in vivo and in vitro bonding study designs have shown that in vitro SBSs are significantly higher than in vivo SBSs.³²

1.6 Adhesive Remnant Index

The Adhesive Remnant Index (ARI) was developed by Artun and Bergland in 1984.^{33,34} It allows the bond failure to be characterized through the amount of remaining adhesive on the tooth following de-bonding. ARI scores the remaining adhesive on the enamel or bracket base by using a 4-point ordinal scale. The teeth are imaged using a stereomicroscope under 50x magnification in order to assess the proper ARI score.

This index has scores that range from 0-3 and the criteria are as follows (Table 1).³⁴

ARI Score	Criteria
0	No adhesive remaining on the tooth
1	<50% of the adhesive remaining on the tooth
2	>50% of the adhesive remaining on the tooth
3	All adhesive remaining on the tooth surface

Table 1 - ARI Scores

Having scores of either 0 or 3 both come with their respective pros and cons. A score of 0 means that there is no adhesive left on the tooth. Minimal amount of enamel removal is required that can decrease chair time during de-bonding. However, this places more stress on the enamel which can lead to enamel damage or enamel loss due to fracture. Conversely, a score of a 3 results in all adhesive remaining on the tooth which protects the tooth from enamel damage, but increases chair time by having to remove the residual adhesive on the tooth.

A disadvantage of ARI is that it is only a qualitative surface area assessment as opposed to a 3-dimensional volumetric measure.³⁵ More detailed surface characteristics will be obtained on randomly selected teeth using a scanning electron microscope. These images will serve as additional observational data.

1.7 Comparison of Groups Selected

This experiment used ninety recently extracted bovine incisors randomly divided into three equal groups (N=30). Each group underwent a different manner of enamel conditioning prior to the bonding of an orthodontic bracket. The methods and materials in which the brackets were bonded to the teeth were all identical. In doing so, only the

enamel conditioning differed such that the experiment evaluated how conditioning affects SBS.

Group A (N=30) was the control, which consisted of treating the enamel with fluoride free pumice followed by 37% acid etch. Currently, this is the most widely accepted and repeated protocol for enamel preparation and conditioning prior to bonding, therefore it was deemed the control.

Group B (N=30) was experimental group one, and conditioned according to the EtchMaster® manufacturers guidelines, which consisted of treating the enamel with air-abrasion followed by 37% acid etch.

Group C (N=30) was experimental group two, and conditioned by treating the enamel only with air-abrasion.

1.8 Purpose

An optimal orthodontic bonding system must minimize damage to the enamel during conditioning, have enough bond strength to prevent bracket de-bonding during treatment, and allow bracket removal at treatment completion, such that minimal damage is inflicted to the tooth.¹ A new approach claims a three-fold increase in bond strength compared to traditional acid etching techniques by substituting air-abrasion in place of pumice prophylaxis prior to acid etching. The purpose of this study is to see if this combination does in fact triple shear bond strength, and if so, what impact it has on the residual enamel surface after de-bonding.

1.9 Specific Aims

Specific Aim 1: Evaluate enamel surface condition (morphology) after conditioning but prior to bonding.

Specific Aim 2: Determine if air-abrasion and phosphoric acid etching results in triple the shear bond strength of pumice prophy and phosphoric acid etching.

Specific Aim 3: Evaluate enamel surface condition after de-bonding for damage characterization.

1.10 Hypotheses

H₀ 1: There is no statistical difference in surface conditions (extent of roughening) of enamel prepared with pumice versus air-abrasion.

H₀ 2: There is no statistical difference in shear bond strength between the group treated with pumice and phosphoric acid versus the group treated with air-abrasion and phosphoric acid.

H₀ 3: There is no statistical difference in the enamel surface condition after de-bonding between the pumice and air-abrasion groups.

1.11 Location of Study

This study was designed and carried out 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

In this *in vitro* experimental study, ninety recently extracted bovine mandibular incisors were randomly divided into three groups of thirty teeth. The facial surfaces were standardized using a polishing wheel. Each group then underwent specific enamel conditioning protocols and the same type of orthodontic bracket was affixed to each tooth. All teeth were then thermocycled and individually mounted into stone blocks. The blocks were placed in a mechanical testing machine for bracket removal. This allowed for measurement of shear bond strength and evaluation of the adhesive remnant index (Figure 1).

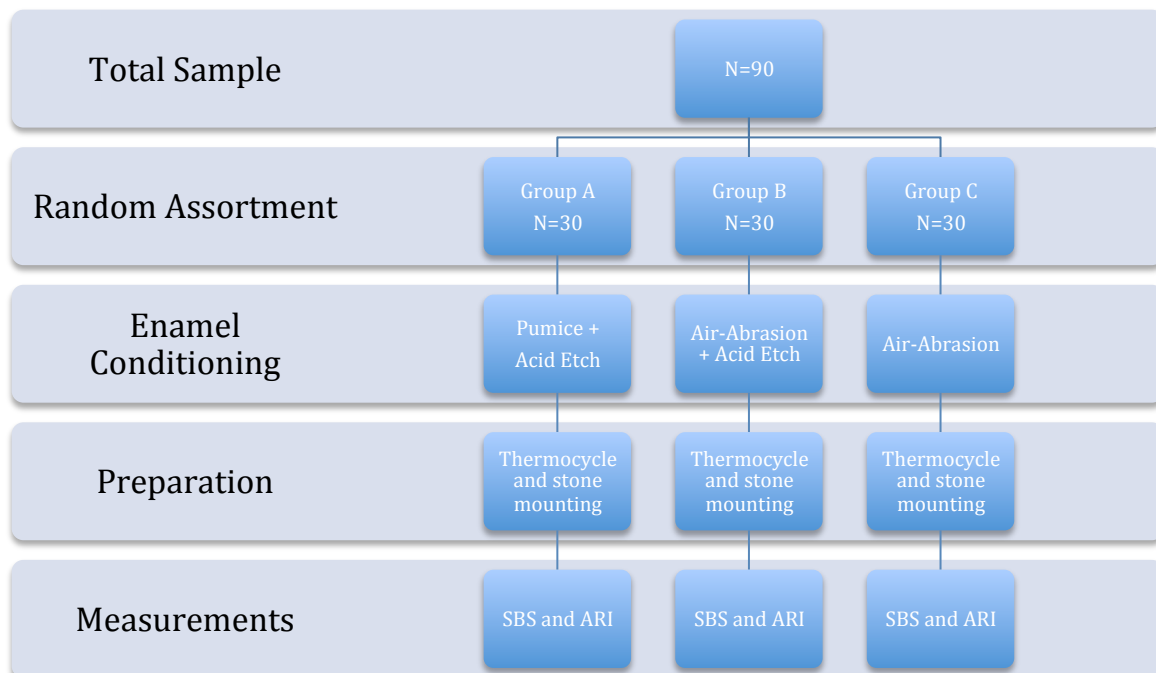


Figure 1. Study Design.

2.2 Sample Acquisition

Twenty-five bovine mandibles were obtained from Adena Farms in Williston, Florida less than one week after slaughter (Figure 2). Immediately upon acquisition, the teeth were extracted. Cows have eight mandibular incisors (Figure 3). These were the teeth utilized in this study. However, not every mandible had eight viable incisors, as several were cracked, broken, or missing. The incisors were extracted using a #2 West periosteal elevator (Henry Schein, Melville, NY), Spear elevator #36 (Henry Schein, Melville, NY), and lower extraction forceps #151A (Henry Schein, Melville, NY).



Figure 2. Lateral View of Bovine Mandible.



Figure 3. Bovine Mandibular Incisors.

The overall research design of this study resembles that of Foersch et al.³⁶ Any and all soft tissue remnants were removed from the incisors with a 0175-HU double-ended scaler (Orthopli, Philadelphia, PA).³⁷ Following extraction, all specimens were stored in a solution of 0.1% (weight/volume) thymol in distilled water at room temperature. The specimens were immersed in this solution for one week, with daily change of the solution.³⁸ Thymol is an antibacterial agent, thus the solution aids in inhibiting bacterial growth. After one week in the thymol solution, the teeth were stored in distilled water. The distilled water was changed daily. No tooth was stored for more than one month after extraction before being conditioned for the study.

The inclusion criteria was that the extracted teeth had no visible caries, were free of significant defects in the enamel that could lead to a compromised bonding surface, and the facial surface was intact (Figure 4). Exclusion criteria for this study include

extracted teeth that had cracks, grooves, or visible enamel imperfections that prevented a uniform bonding surface.



Figure 4. Bovine incisors of various sizes.

2.3 Groups

Of the 138 teeth obtained, 98 met the inclusion criteria. In addition to the clinical crown being intact, a root of sufficient length was required. This was necessary such that the tooth would have adequate stability for bond strength testing once mounted in a stone block. 90 teeth were then randomly assigned into three groups of 30 (Figure 5).

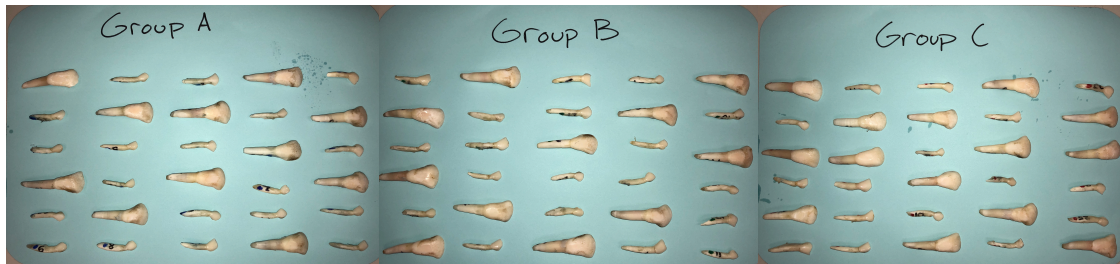


Figure 5. Experimental Groups A, B, and C.

2.4 Enamel Standardization

Due to surface topography variation amongst the bovine teeth, flattening of the enamel surface was indicated. This created a standardized surface in which the discrepancies between teeth were eliminated and the study could be conducted with greater uniformity. Previous bonding studies that utilized bovine teeth ground the facial enamel using a polishing wheel with progressive 320, 400, and 600-grit silicon carbide (SiC) paper under running water.^{39,40} This study utilized the same protocol. All ninety teeth were smoothed on a Metaserv 2000 Grinder/Polisher (Buehler UK LTD., Coventry, England; Figure 6 and 7) at 500 RPM under running water for five seconds. The teeth were ground progressively using 320, 400, and 600-grit SiC 8-inch diameter abrasive paper (Buehler UK LTD., Coventry, England; Figure 8).



Figure 6. Metaserv 2000 Grinder.



Figure 7. Facial surface of incisor being flattened.

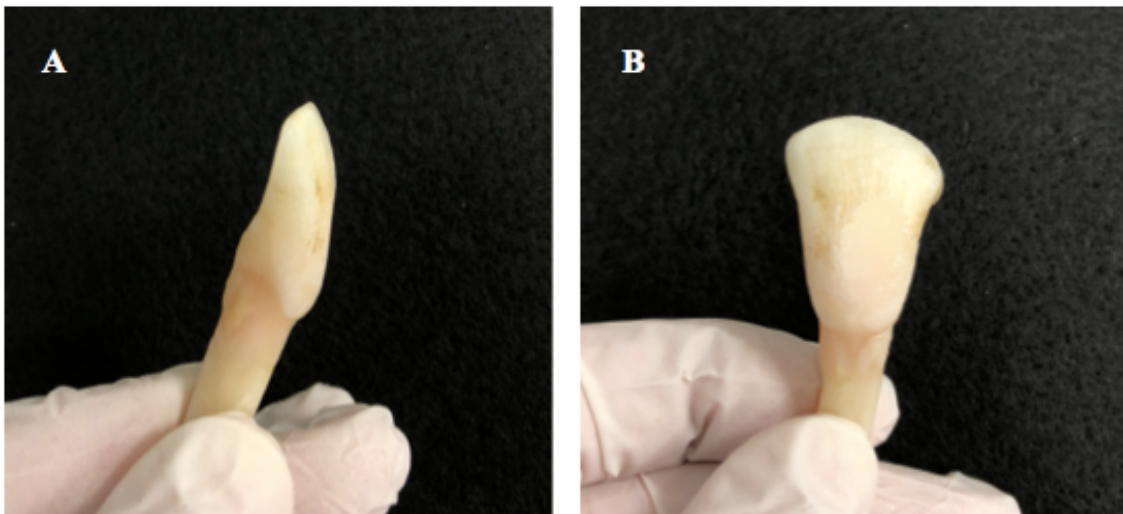


Figure 8. Picture A shows the flattening from a mesial/distal aspect. Picture B shows the flattened facial surface.

2.5 Brackets

All teeth had the same orthodontic bracket bonded to the facial surface. The American Orthodontics Master Series System twin MBT mandibular incisor bracket

(Sheboygan, WI, USA; Figure 9) was selected for both bracket base size and flatness considerations. As there was significant variation in the anatomical crown of the bovine incisors, a bracket that had a small surface area was indicated. Additionally, as the teeth were ground flat for standardization, a bracket base that had minimal convexity was ideal. For these purposes, the mandibular incisor bracket was best suited.



Figure 9. The American Orthodontics Master Series System twin MBT mandibular incisor bracket.

2.6 Micro Air-Abrasion

All air-abrasion conducted in this study utilized the EtchMaster® (Groman Dental, Margate, FL; Figure 10). The single use disposable tip contains pre-packaged 50-micron (μm) aluminum oxide. The EtchMaster® was operated according to manufacturer's instructions. For orthodontic bonding, 50 μm aluminum oxide powder was used at 40 psi at a distance of 1 mm from the enamel surface. The exposure time was approximately three seconds, the time required to sweep the nozzle over the bonding surface.

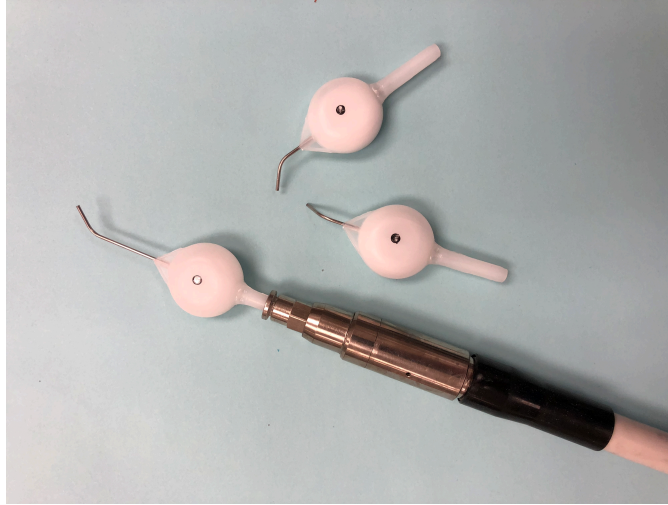


Figure 10. Etchmaster® with 50 μm tip.

2.7 Curing Light

All light curing was done using the same Valo® Ortho curing light (Ultradent, South Jordan, UT) under manufacturer's instructions. The light has a wavelength of approximately 395-480 nm and a maximum intensity of up to 3200 mW/cm². The intensity was maintained between 1950-2100 mW/cm² at a distance of 2-3 millimeters from the bracket. The curing light was calibrated using a LEDex cm4000 radiometer (SDI, Victoria, Australia) that measures up to 4000 mW/cm² (Figure 11). Measurements were obtained, prior to bonding, and periodically throughout the experiment to ensure consistent intensity.



Figure 11. Radiometer with curing light measuring mW/cm^2 .

2.8 Group A

Group A consisted of thirty teeth. A ten second rubber cup prophylaxis of the teeth was done using Nanda® medium grit fluoride free prophy paste (Preventech, Indian Trail, NC; Figure 12). The teeth were then rinsed for ten seconds with distilled water at room temperature and dried for two seconds with a moisture-free and oil-free air stream such that all pumice residues were removed from the tooth.



Figure 12. Fluoride-free pumice of enamel surface.

Next, 37% phosphoric acid gel (Kerr, Orange, CA) was applied to the buccal surface for thirty seconds, and then thoroughly rinsed with distilled water at room temperature for ten seconds. The surface was then dried with a moisture-free and oil-free air source for ten seconds, giving the enamel a chalky white appearance. Assure bonding resin (Reliance Ortho, Itasca, IL) was applied onto the enamel surface using a microbrush in a thin coat, and then thinned with moisture-free and oil-free air for five seconds, followed by a three second light cure. A thin layer of Transbond™ XT adhesive (3M Unitek, Monrovia, CA) was applied to the bracket base, and then the bracket was placed on the conditioned enamel surface. The brackets were seated using a 300 gm perpendicular force measured with a dontrix gauge (Orthopli, Philadelphia, PA; Figure 13). Visible flash was then removed with an #23 explorer instrument (Orthopli, Philadelphia, PA). The bracket was light cured, three seconds from the mesial aspect, and three seconds from the distal aspect using a Valo® Ortho curing light.

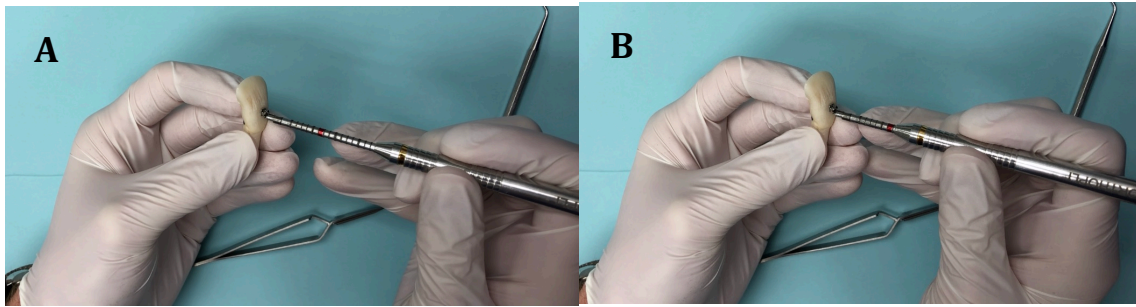


Figure 13. Picture A shows a donatrix gauge positioned on the bracket. Picture B shows the 300 gram seating force.

2.9 Group B

Group B consisted of thirty teeth. The teeth were air-abraded using the EtchMaster® at 40 psi at a distance of 1 mm from the enamel surface (Figure 14). The exposure time was approximately three seconds, the time required to sweep the nozzle over the bonding surface. The teeth were then rinsed for ten seconds with distilled water at room temperature and dried for two seconds with a moisture-free and oil-free air stream to ensure all aluminum oxide residues were removed from the tooth.

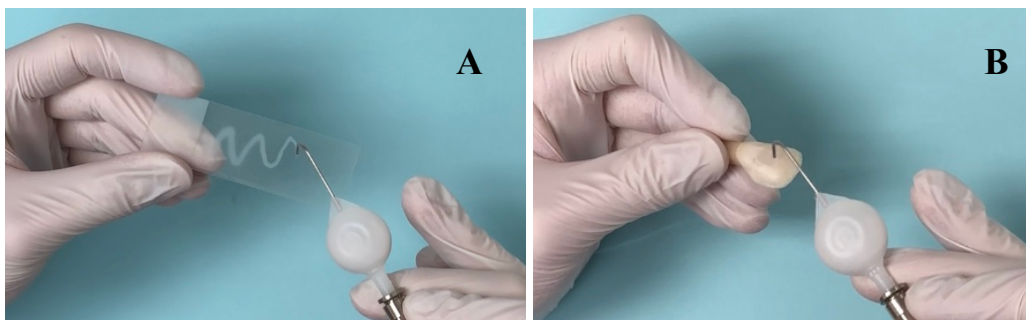


Figure 14. Picture A shows Etchmaster® demonstrates the air-abrasion on a glass slab. Picture B is the Etchmaster® on the enamel surfaces.

Next, 37% phosphoric acid gel (Kerr, Orange, CA) was applied to the buccal surface for thirty seconds, and then thoroughly rinsed with distilled water at room

temperature for ten seconds. The surface was then dried with a moisture-free and oil-free air source for ten seconds, giving the enamel a chalky white appearance. Assure bonding resin (Reliance Ortho, Itasca, IL) was applied onto the enamel surface using a microbrush in a thin coat, and then thinned with moisture-free and oil-free air for five seconds, followed by a three second light cure. A thin layer of Transbond™ XT adhesive (3M Unitek, Monrovia, CA) was applied to the bracket base, and then the bracket was placed on the conditioned enamel surface. The brackets were seated using a 300 gm perpendicular force measured with a dontrix gauge (Orthopli, Philadelphia, PA). Visible flash was then removed with an #23 explorer instrument (Orthopli, Philadelphia, PA). The bracket was light cured, three seconds from the mesial aspect, and three seconds from the distal aspect using a Valo® Ortho curing light.

2.10 Group C

Group C consisted of thirty teeth. The teeth were air-abraded using the EtchMaster® at 40 psi at a distance of 1 mm from the enamel surface. The exposure time was approximately three seconds, the time required to sweep the nozzle over the bonding surface. The teeth were then rinsed for ten seconds with distilled water at room temperature and dried for ten seconds with a moisture-free and oil-free air stream to ensure all aluminum oxide residues were removed from the tooth.

Assure bonding resin (Reliance Ortho, Itasca, IL) was applied onto the enamel surface using a microbrush in a thin coat, and then thinned with moisture-free and oil-free air for five seconds, followed by a three second light cure. A thin layer of Transbond™ XT adhesive (3M Unitek, Monrovia, CA) was applied to the bracket base, and then the

bracket was placed on the conditioned enamel surface. The brackets were seated using a 300 gm perpendicular force measured with a dontrix gauge (Orthopli, Philadelphia, PA). Visible flash was then removed with an #23 explorer instrument (Orthopli, Philadelphia, PA). The bracket was light cured, three seconds from the mesial aspect, and three seconds from the distal aspect using a Valo® Ortho curing light.

2.11 Thermocycling

Following bonding, all teeth were stored in distilled water at thirty-seven degrees Celsius for twenty-four hours prior to thermocycling. The teeth were placed in the Thermocycling Test Apparatus (Sabri Dental Enterprises, Downers Grove, IL) for five hundred cycles in water baths set at five degrees Celsius and fifty-five degrees Celsius (Figures 15 and 16).³⁸ Each cycle consisted of thirty seconds dwell time in each bath with a three second transfer time between baths. All groups were thermocycled at the same time. Each group was in a labeled cheesecloth pouch with an attached weight to insure complete submersion. Following thermocycling, all teeth were again stored in distilled water at thirty-seven degrees Celsius until mounted.



Figure 15. Thermocycling Test Apparatus.

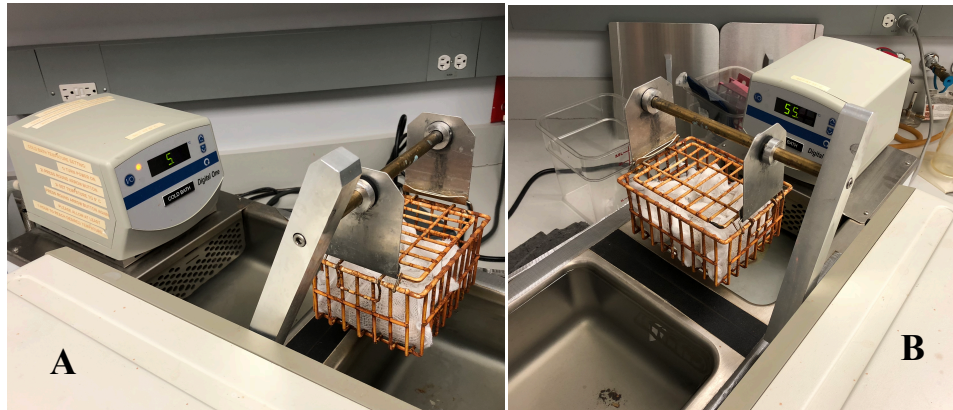


Figure 16. Picture A shows the cold water bath set at 5° Celsius with the teeth in the basket. Picture B shows the warm water baths at 55° Celsius.

2.12 Tooth Mounting

All teeth were then individually mounted into Microstone Golden ISO Type 3 (Whip Mix, Louisville, KY) blocks, size 35x35x35 mm using silicone trays (Figure 17). Teeth were mounted such that the occlusal aspect of the bracket was parallel to the floor and the buccal surface of the tooth was perpendicular to the floor (Figure 15). This was done to insure the blade on the Universal Testing Machine Model 8841 (Instron, Canton, MA) would contact the bracket at the appropriate orientation. Each group was then

placed in a sealable container filled with distilled water and stored at thirty-seven degrees Celsius (Figures 18 and 19).

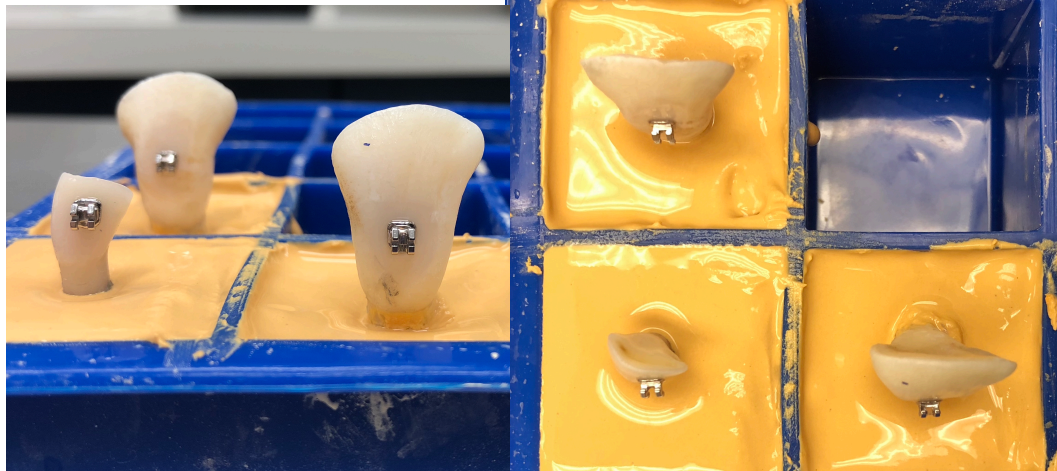


Figure 17. Brackets bonded parallel such that Instron blade can properly engage.



Figure 18. Teeth mounted in blocks.

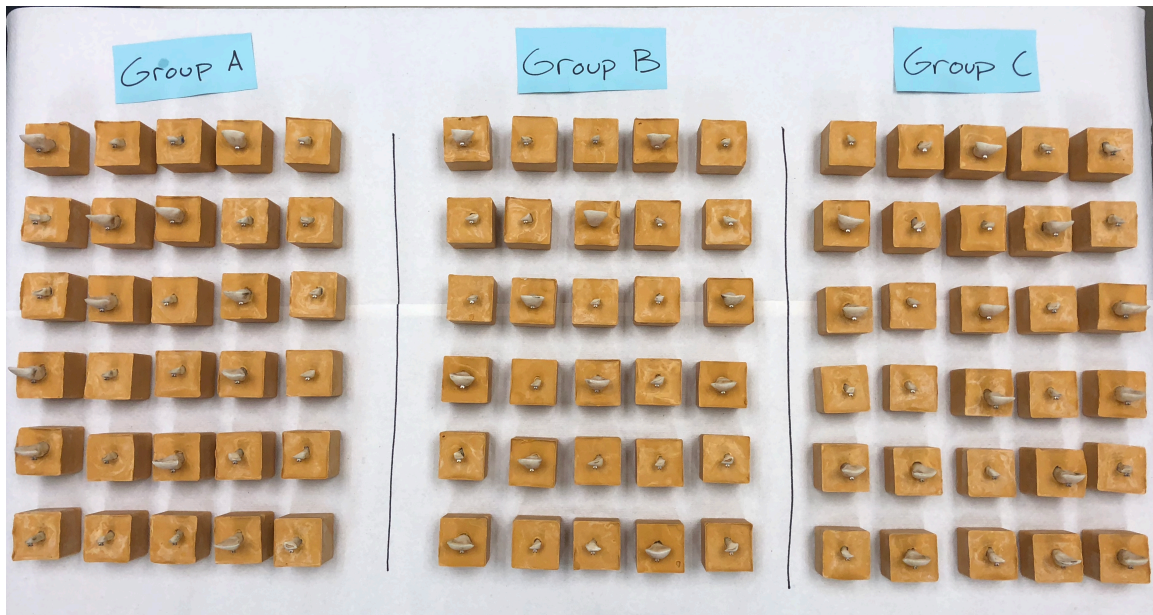


Figure 19. All groups individually mounted.

2.13 De-bonding

A Universal Testing Machine Model 8841 (Instron, Canton, MA) was utilized to determine the shear bond strength (SBS). As described by Zeppierei et al.⁴¹ 2003, a metal chisel was oriented perpendicular to the top of the bracket and parallel to the buccal surface of the tooth which produced an occluso-gingival force at the bracket-tooth interface to de-bond the brackets (Figure 20).



Figure 20. The instron blade is positioned above the bracket.

The chisel operated with a one thousand Newton (N) load cell at a crosshead speed of 5.0 mm/min (Figure 21).⁴² The maximum force required to produce bond failure was reported in Newtons (N) and subsequently converted, using the area of the bracket base, to megapascals (MPa) to determine the SBS. In order to convert N to MPa, the measured force was divided by the mean surface area of the bracket base, 8.42 mm² (Figure 22). All teeth had brackets de-bonded and SBS calculated. Again, each group was then placed in a sealable container filled with distilled water and stored at thirty-seven degrees Celsius.



Figure 21. Instron machine.



Figure 22. Mounted tooth with de-bonded bracket.

2.14 Adhesive Remnant Index

The modified adhesive remnant index (ARI) allows the bond failure mode to be observed through the amount of remaining adhesive left on the tooth following de-bonding. The ARI is clinically important as it indicates where bond failure occurs.⁴³

Failures at the enamel-adhesive interface are the most concerning because major stress at this site can damage the enamel.³³ Following de-bonding, each tooth and bracket was imaged on a SZX7 Stereomicroscope System under 50x magnification (Olympus, Center Valley, PA), evaluated, and assigned an ARI score (Figure 23). The ARI is graded on a scale from 0-3 (Table 2).^{34,44} Examples of each score are seen below in Figures 24-27.



Figure 23. Stereomicroscope with tooth on glass slide.

ARI Score	Criteria
0	No adhesive remaining on the tooth
1	<50% of the adhesive remaining on the tooth
2	>50% of the adhesive remaining on the tooth
3	All adhesive remaining on the tooth surface

Table 2. ARI Grading Scale.

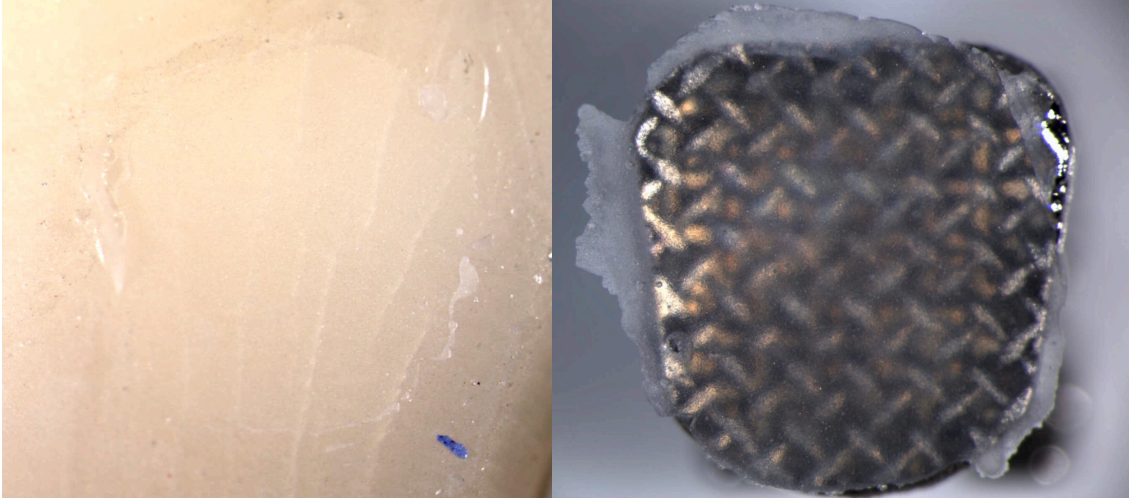


Figure 24. Example of ARI score 0, no adhesive remaining on the tooth surface (50x magnification).

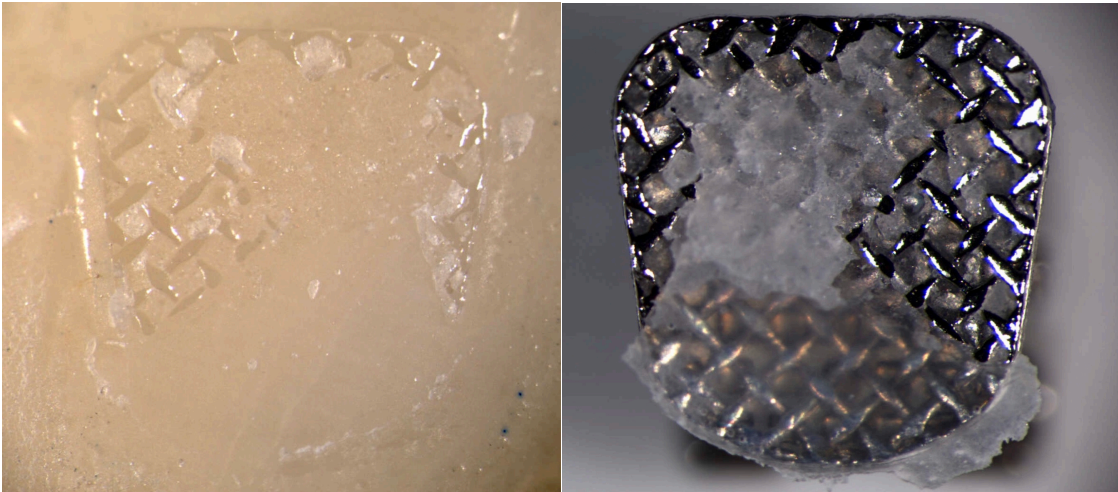


Figure 25. Example of ARI score 1, less than 50% adhesive remaining on the tooth surface (50x magnification).

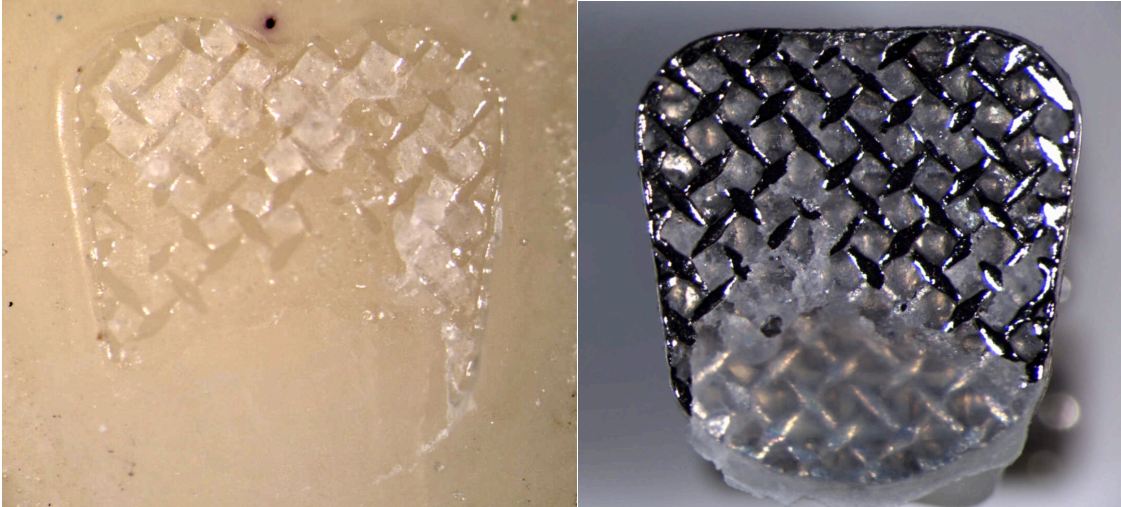


Figure 26. Example of ARI score 2, more than 50% adhesive remaining on the tooth surface (50x magnification).

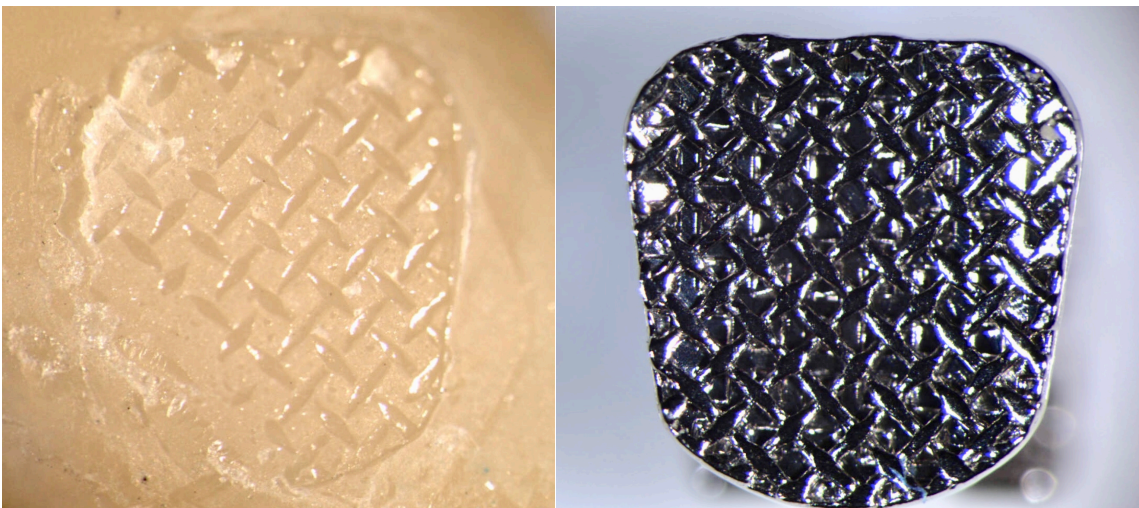


Figure 27. Example of ARI score 3, all adhesive remaining on the tooth surface (50x magnification).

2.15 Observational Imaging

Five teeth were randomly selected from each group to observe and analyze enamel surface topography. For each tooth, images were obtained on the virgin tooth surface, following enamel smoothing, after surface conditioning, and after bracket de-bond. These teeth were imaged using the SZX7 Stereomicroscope System at various

magnifications. Additional images were obtained using a Quanta 200 Scanning Electron Microscope (FEI, Hillsboro, OR; Figure 30). In order to prepare the teeth for SEM imaging, they first needed to be sputter-coated with gold to increase electron conductivity (Cressington Sputter Coater 108auto, Ted Pella, INC., Redding CA; Figures 28 and 29).

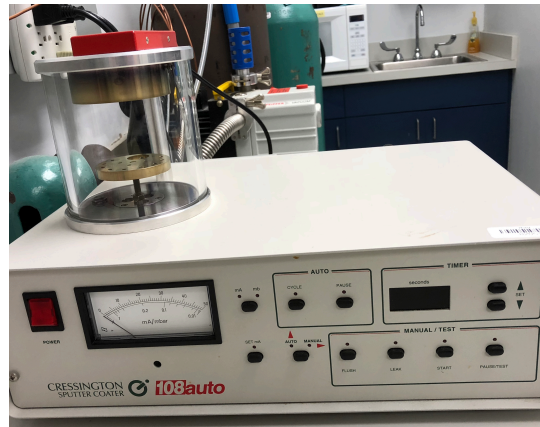


Figure 28. Sputter coating instrument.



Figure 29. Samples before and after sputter coating

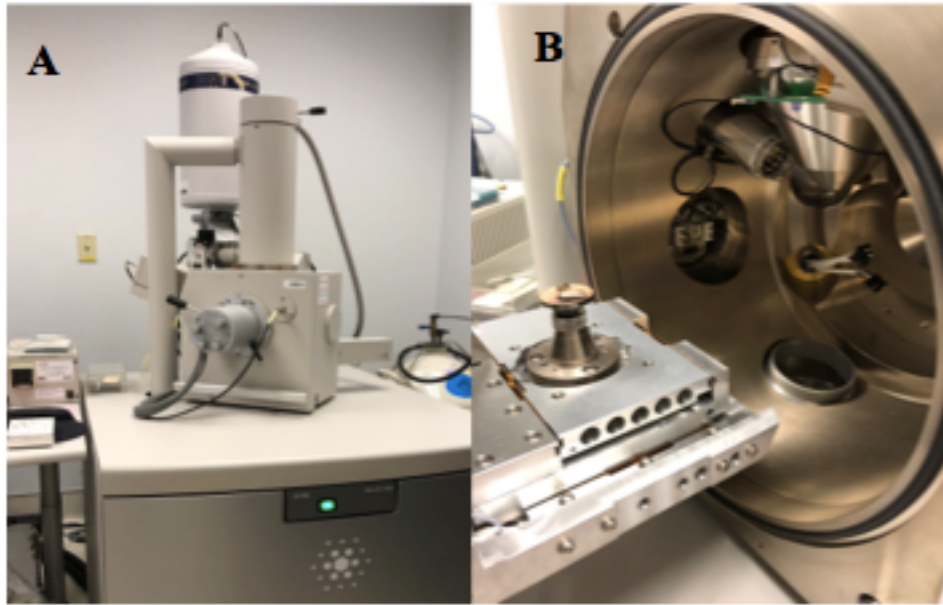


Figure 30. Picture A shows the SEM machine. Picture B shows the sputter-coated sample being loaded into the chamber.

2.16 Statistical Analysis

Descriptive statistics were calculated for all study variables. This includes means and standard deviations for continuous measures, and counts and percentages for categorical data. To test the difference between groups for ARI scores, Fisher's Exact test was used. Pairwise comparisons were performed using a Tukey adjustment. Effect size estimates included intra-class correlations, Cramer's V, and relevant 95% confidence intervals. RStudio and R 3.2.2 were used for all statistical analyses. Statistical significance was accepted at $p < 0.05$.

Chapter 3: Results

3.1 Shear Bond Strength

Analysis of variance showed a main effect of Group on SBS (MPa), $F(2, 87) = 60.66$, $p < 0.001$, $\eta^2 = 0.58$. Post-hoc analyses using Tukey's HSD indicated that debonding forces were higher for teeth in Group A (P+AE) than in Group C (AA) ($p < 0.001$), teeth in Group B (AA+AE) than in Group C ($p < 0.001$), but not different between teeth in Group A and Group B ($p = 0.981$) (Tables 3, 4 & Figure 31).

	MPa				
	Sum Sq	Df	F value	Pr(>F)	Partial Eta Squared
(Intercept)	13895.46	1	458.39	0.00	0.84
Group	3677.63	2	60.66	0.00	0.58
Residuals	2637.28	87	NA	NA	NA

Table 3. ANOVA comparison of Shear Bond Strength data.

	MPa			
Group	Mean Difference	P-Value	Lower 95% CI	Upper 95% CI
A - B	-0.31	0.97	-3.09	2.48
A - C	13.40	≤ 0.0001	10.62	16.19
B - C	13.71	≤ 0.0001	10.93	16.50

Table 4. Tukey HSD pairwise comparisons of SBS means and standard deviations.

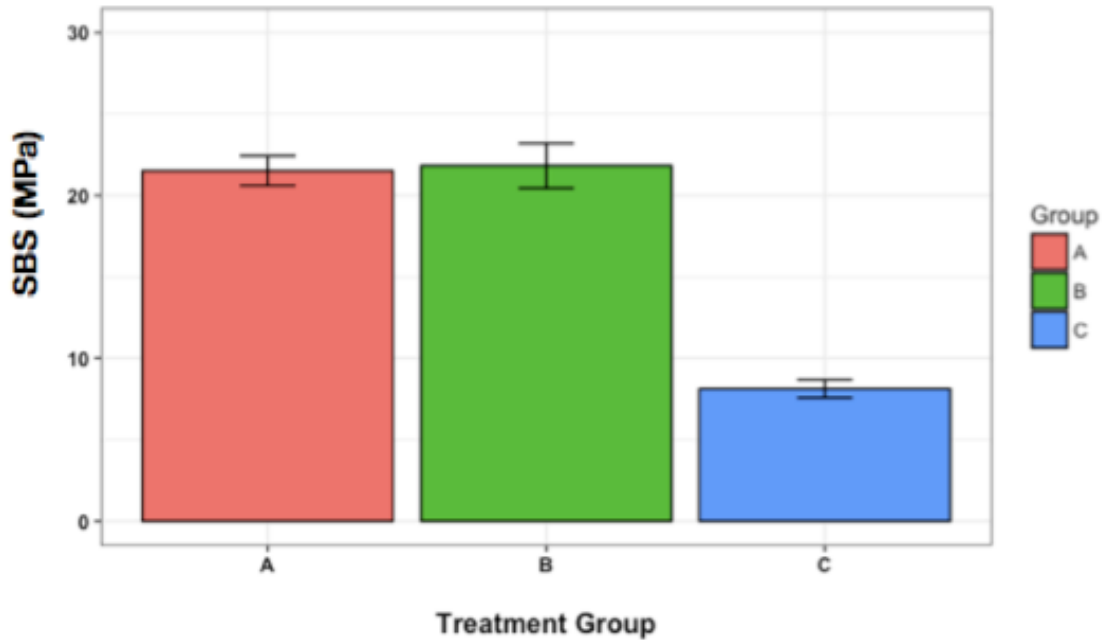


Figure 31. Tukey HSD test (SBS data) with standard error bars.

3.2 Adhesive Remnant Index

Results from the Fisher’s Exact test, where we controlled the Type I error using a Bonferroni correction, reveals that ARI scores differed by group ($p < 0.001$) (Table 5 & Figure 33).

- Group A (P+AE) had significantly more scores of 0 than Group B ($p < 0.001$).
- Group A (P+AE) had significantly more scores of 1 and 2 than Group C ($p < 0.001$).
- Group B (AA+AE) had significantly more scores of 1 and 2 than Groups A and C ($p < 0.001$).
- Group C (AA) had significantly more scores of 0 than Groups A and B ($p < 0.001$).

	0	1	2	3
A	14 (0.47)	10 (0.33)	5 (0.17)	1 (0.03)
B	3 (0.10)	16 (0.53)	10 (0.33)	1 (0.03)
C	29 (0.97)	1 (0.03)	0 (0.00)	0 (0.00)

Table 5. Descriptive statistics for ARI data measures

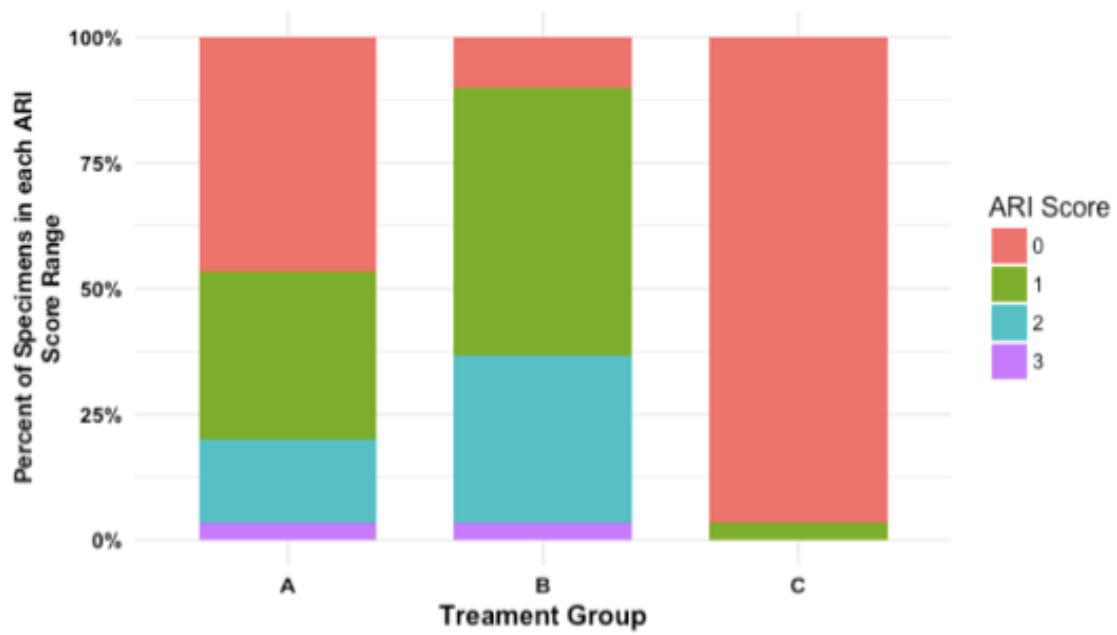


Figure 32. ARI score breakdown by percentage.

Chapter 4: Discussion

4.1 Shear Bond Strength

Based on the results of this study, we accept the null hypothesis that there is no statistical difference in shear bond strength between Group A treated with pumice and acid etch (P+AE) versus Group B treated with air-abrasion and acid etch (AA+AE). As is evident in the table below, the mean SBS was nearly identical in both the pumice and the air-abrasion groups (Table 6). Even the maximum value obtained by Group B (AA+AE) does not equal twice the mean of the control Group A (P+AE). It is clearly evident that the method of substituting air-abrasion using the EtchMaster® for pumice will not triple the SBS. This finding is consistent with that of Reisner et al.¹⁸ The air-abrasion plus acid etchant group was found to have the greatest de-bonding force, although differences were not statistically significant compared to the pumice and acid etchant group.

MPa				
Group	M	SD	Min	Max
A (N = 30)	21.52	4.97	9.12	30.74
B (N = 30)	21.83	7.55	0.00	36.67
C (N = 30)	8.12	3.05	1.90	12.59

Table 6. Descriptive statistics for continuous measures

The above table also confirms what previous studies concluded, such as Olsen et al.¹⁷, that air-abrasion alone is not clinically acceptable as an enamel conditioner prior to bracket bonding. As stated earlier, a SBS of about 15 MPa is necessary to withstand the forces generated in the oral cavity.³⁰ Group C, air-abrasion only (AA), had a mean SBS of only 8.12 MPa, about half of the required strength. It remains true that at this point in time, treatment of the enamel surface with air-abrasion alone is not a sufficient preparation method for orthodontic bonding.

The acid etch is a vital step in enamel conditioning as it creates micro-scale roughness in the enamel surface. This in turn allows for a greater spread and penetration of the low-viscosity resin adhesive.⁴⁵ Once the resin is polymerized, it is adhered to the enamel surface via mechanical interlocking. It is these resin extensions into the crystalline structure of the enamel micro-features that is the mechanism responsible for the bond strength.⁴⁶

4.2 Adhesive Remnant Index

The manner in which the bond is broken between the enamel and the bracket is just as important as its SBS. The ARI is clinically important as it indicates where bond failure occurs.⁴³ Failures at the enamel-adhesive interface are the most concerning because major stress at this site can damage the enamel.³³ If the bond strength is too high, the enamel and composite interface may remain intact but ditching, fracture, or disruption of the surface structure could damage the underlying enamel. Similarly, if the bond strength is too great, the bracket and composite interface can fracture and leave the majority of resin on the tooth. While this situation is safer for the enamel, it leads to an

increase in time required to remove the composite and potential for iatrogenic damage during removal.

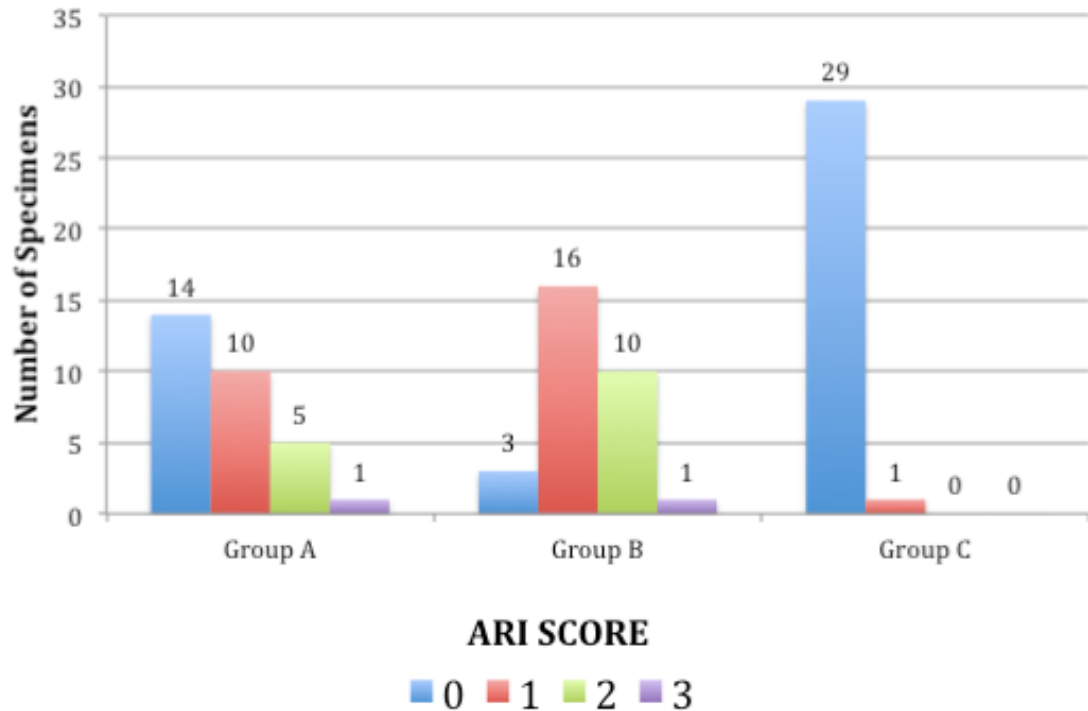


Figure 33. ARI Data.

Group A (P+AE) and Group B (AA+AE) only had one specimen each, or three percent, which had an ARI score of three (Tables 5 and Figure 33). An ARI of three indicates all composite remained on the enamel surface. Ninety-seven percent of Group C (AA) had a score of zero, indicating there was no adhesive remaining on the tooth. The study by Olsen et al.¹⁷ found similar results with the air-abrasion only group. This finding further confirms that an inadequate bond is formed when conditioning enamel with air-abrasion only.

The majority of Group A (P+AE), forty-seven percent, also had an ARI score of zero. Group C had significantly more scores of zero than Groups A and B, but Group A

also had significantly more scores of zero than Group B. This is interesting, as we know the mean SBS of Groups A and B were virtually equal. Fifty-three percent of Group B (AA+AE) had a score of one, meaning less than fifty percent of the resin remained. Thirty-three percent of Group B had more than fifty percent of the resin present on the enamel surface, a score of two.

Despite having nearly identical mean SBS's, statistically significant differences in ARI scores exist. It is unknown what could have caused these differences. Perhaps air-abrasion removed surface debris more effectively than pumice that resulted in less biofilm or surface contaminants. This could have led to a stronger bond at the enamel interface that resulted in bond failure occurring at both the bracket and enamel interface under similar load. Additional outliers may be attributed to contamination issues after etchant application.

4.3 Observational Images

Five teeth were randomly selected from each group to observe and analyze enamel surface topography. Images were obtained at different time points throughout the study. These teeth were imaged using the SZX7 Stereomicroscope System at various magnifications. Additional images were obtained using a Quanta 200 Scanning Electron Microscope.

4.4 Virgin Enamel versus Flattened Enamel

As seen below (Figures 34 & 35) the enamel surface is slightly altered during the flattening process. The sheen of the virgin enamel is not replicated in the flattened

enamel. Perhaps most important aspect of the virgin enamel is the variations in surface topography. The minor pits, cracks, and unique characteristics are readily visible at 38.75x magnification. The flattened, or ground enamel, lacks the high polish shine of the virgin, but has a uniformly flat surface. Very minor striation patterns are visible from the silicon carbon polishing discs.

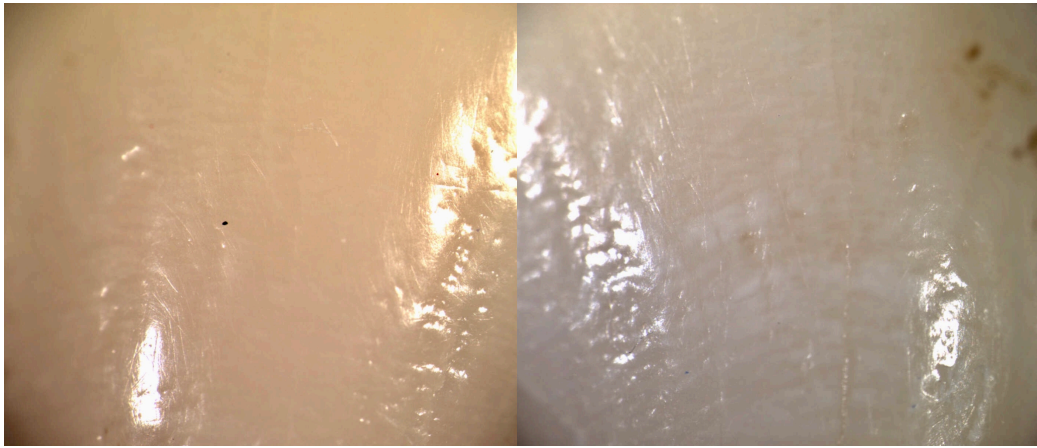


Figure 34. Virgin teeth at 38.75x magnification.



Figure 35. Flattened teeth at 38.75x magnification.

4.5 Post Enamel Conditioning

Stereomicroscopic images were again obtained following each group's specific conditioning regimen. The images in Figure 36 show a slight chalkiness and less reflective surface as compared to Figure 35. Groups A (P+AE) and B (AA+AE) are almost indistinguishable however Group C (AA) has visual differences. Group C has some speckled reflective properties that appear to be residual aluminum oxide particles that did not rinse off.

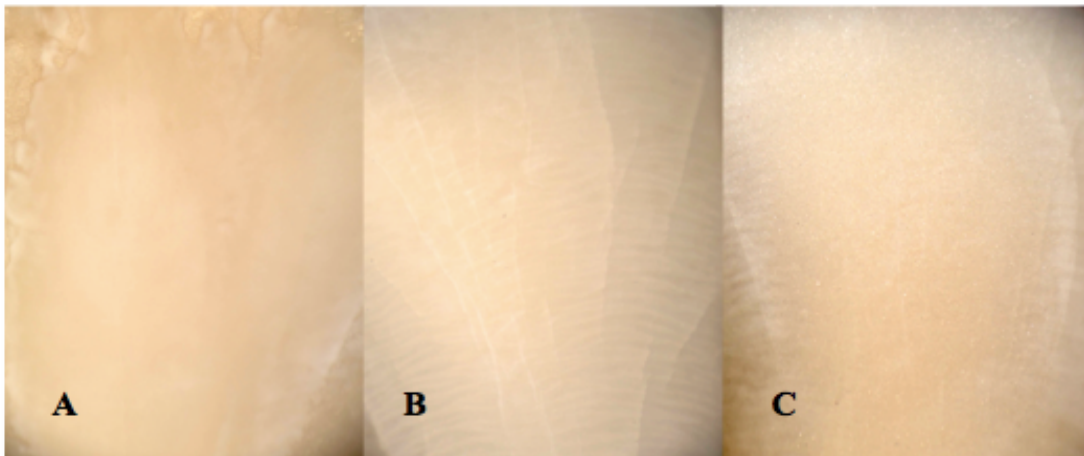


Figure 36. Each group following conditioning protocol at 38.75x magnification.

4.6 Post De-Bond

As seen in the images below, residual resin is easily identified. Table 5 above lists the percentage of each group's ARI score. Below are representative examples of what the bulk of each group's enamel looked like following de-bond. No enamel defects were observed on the tooth or on the resin that was retained on the bracket pad.

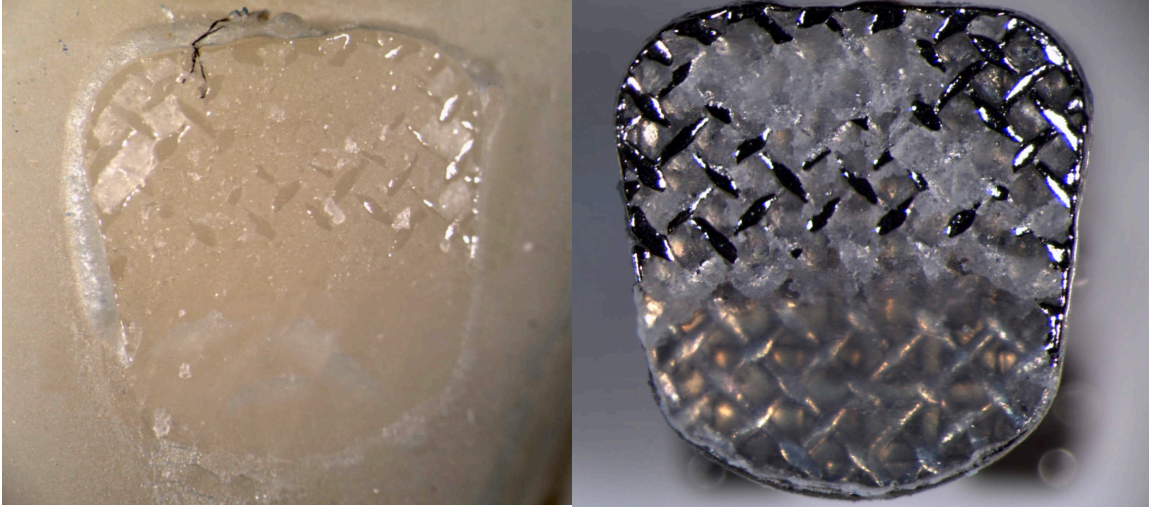


Figure 37. Group A following de-bond at 50x magnification.

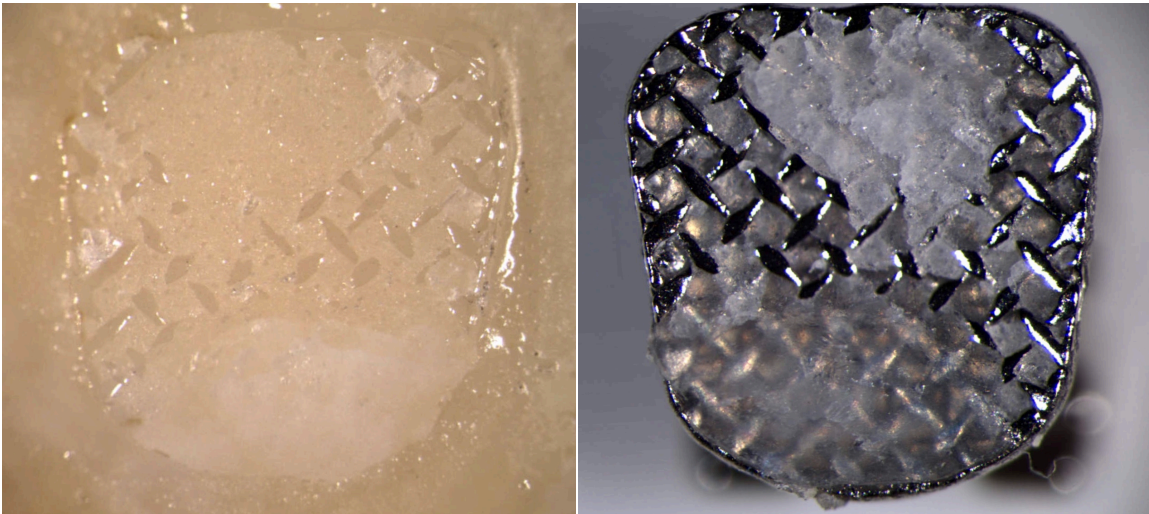


Figure 38. Group B following de-bond at 50x magnification.

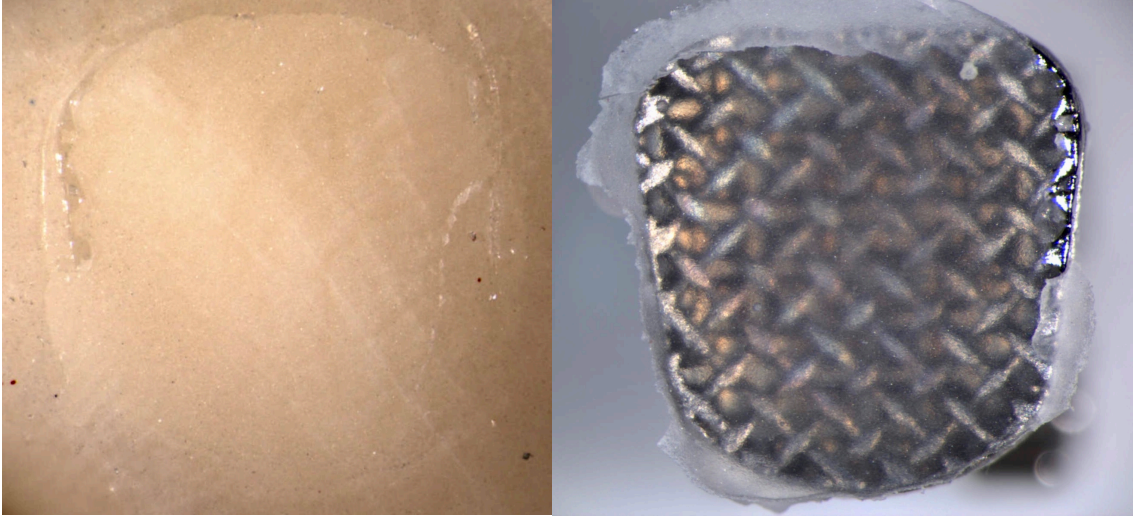


Figure 39. Group C following de-bond at 50x magnification.

4.7 SEM Images

One sample was randomly selected from each group for SEM imaging. Post conditioning and post de-bond were imaged. The process of sputter coating requires complete desiccation of the specimen. This drying process caused the surface cracks seen in some of the images below, the bracket being de-bonded did not cause them.

The conditioned Groups A (P+AE) and B (AA+AE) show a similar topography of what appears to be exposed enamel rods. Group C (AA) has a much less roughened and exposed surface that does not look consistent with that of the other groups. That surface morphology allows for a stronger bond due to resin penetration into the micro-roughness, and is the reason why Groups A and B had an average SBS more than twice that of Group C.

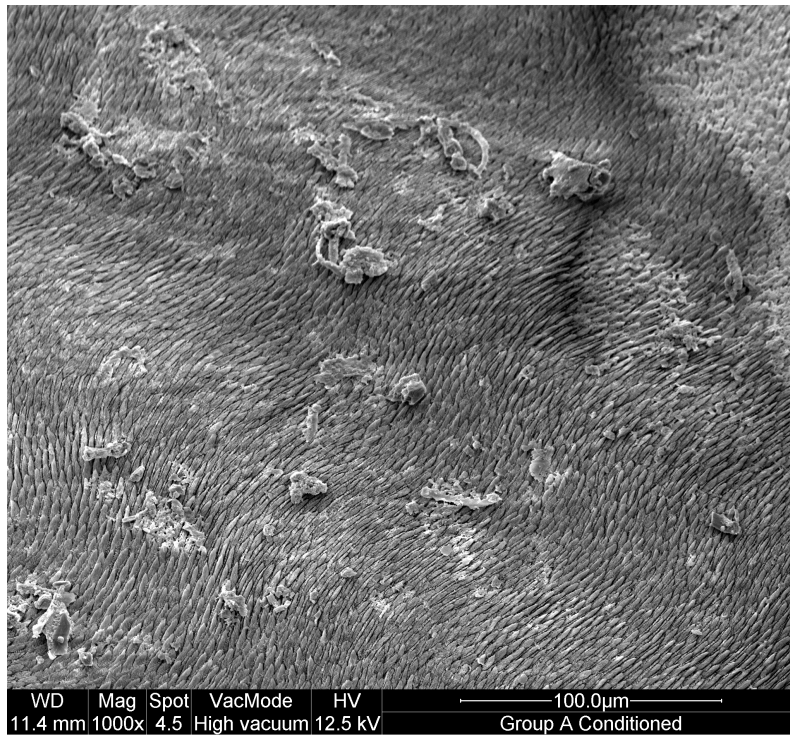


Figure 40. SEM image at 1000x of Group A after conditioning.

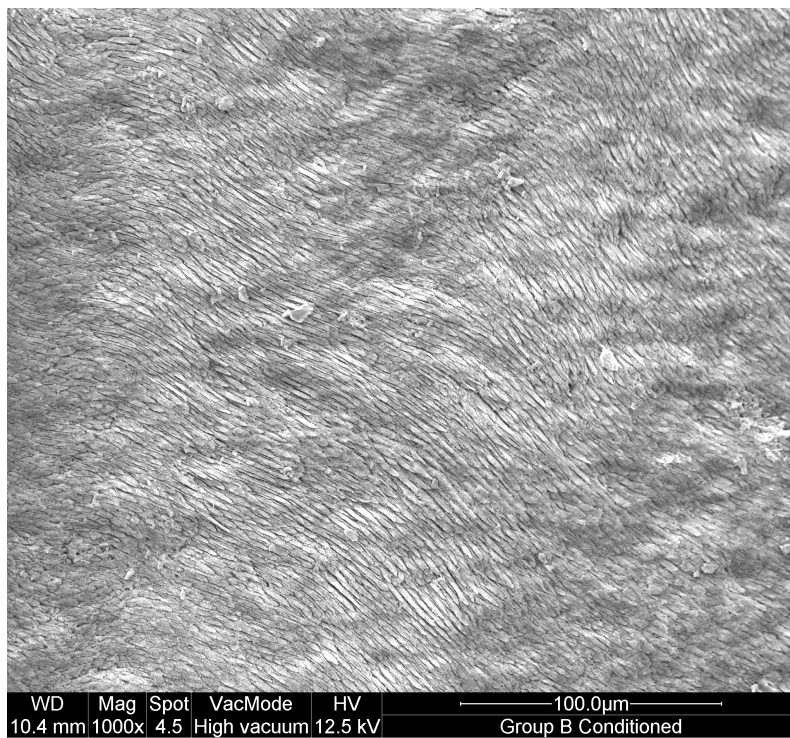


Figure 41. SEM image at 1000x of Group B after conditioning.

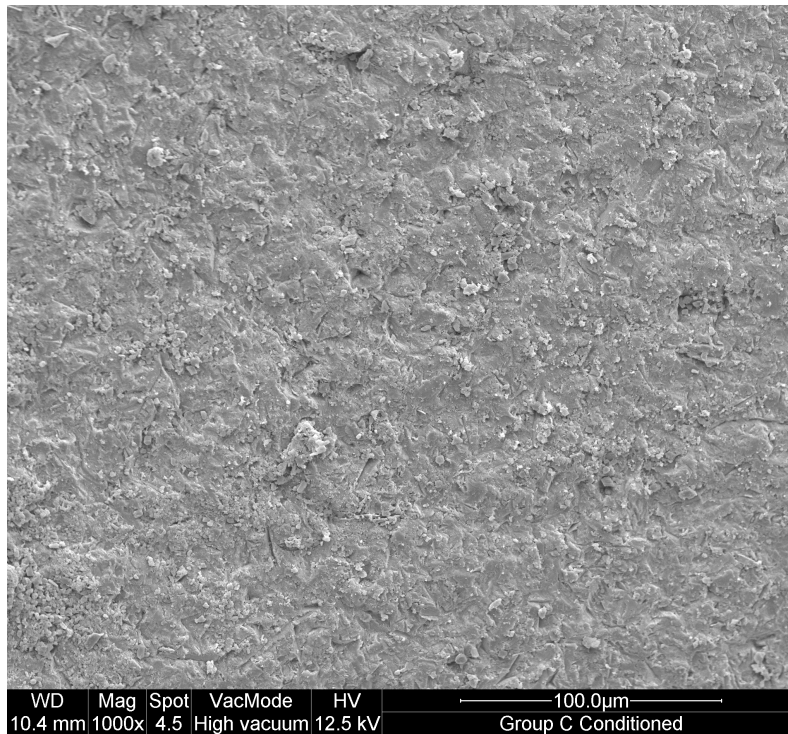


Figure 42. SEM image at 1000x of Group C after conditioning.

The SEM images of the enamel following de-bond further confirm the previous data obtained from this study. Groups A (P+AE) and B (AA+AE) have a significant portion of resin remaining on the tooth while Group C (AA) has almost none. The exposed enamel in all sample groups shows no signs of damage. The images below add additional support that air-abrasion in lieu of pumice creates almost identical results, while air-abrasion alone produces an insufficient SBS for orthodontic use.

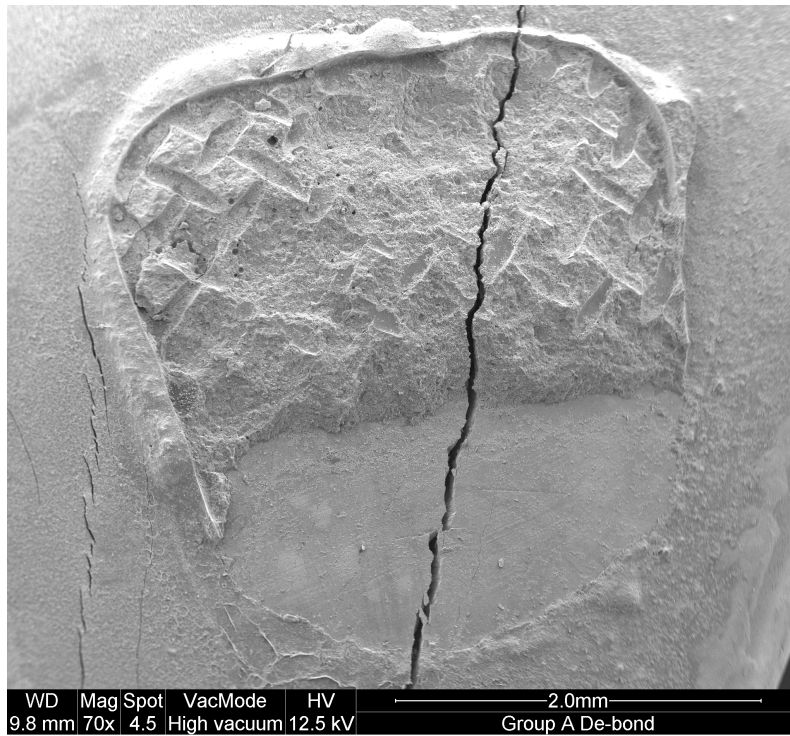


Figure 43. SEM image at 70x of Group A after de-bond.

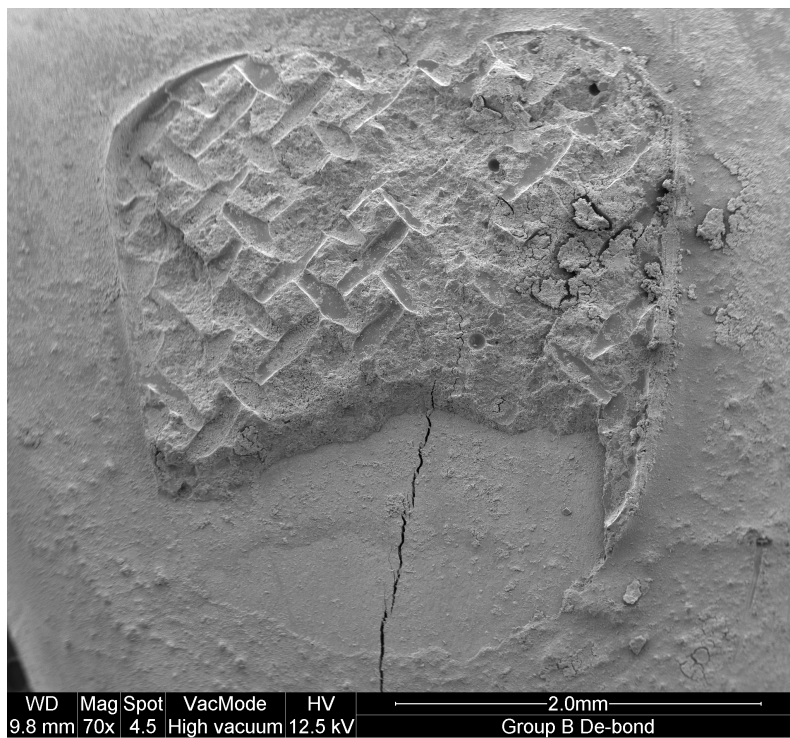


Figure 44. SEM image at 70x of Group B after de-bond.

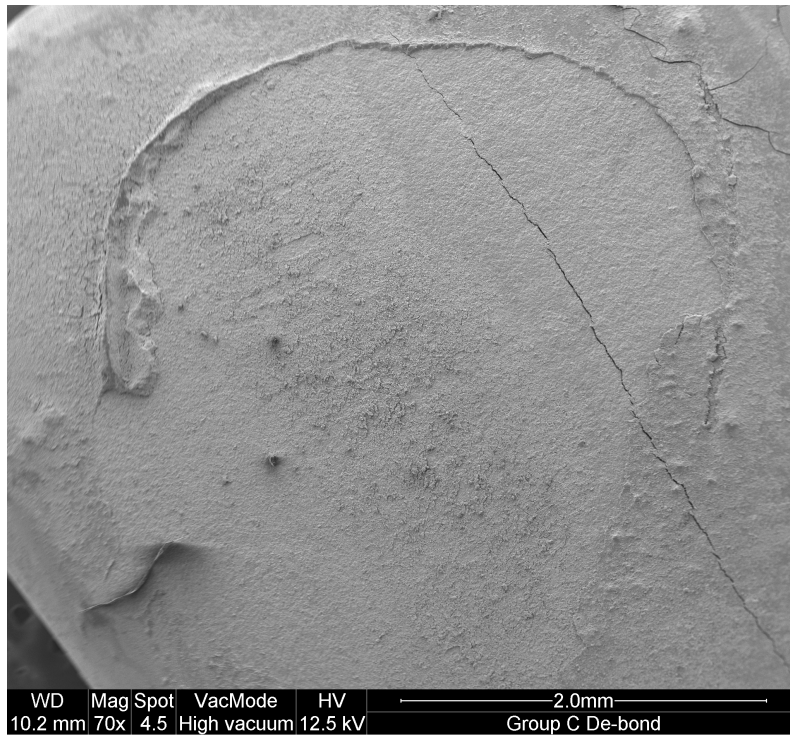


Figure 45. SEM image at 70x of Group C after de-bond.

Chapter 5: Conclusion

Within the limitations of this *in vitro* study, we can conclude that air-abrasion in lieu of pumice prior to acid etching does not significantly increase shear bond strength. It remains abundantly clear that the critical step in enamel preparation prior to orthodontic bonding is application of acid etchant. Conditioning with the use of air-abrasion only results in insufficient bond strength. This is observed by looking at both the shear bond strength and the ARI score.

Despite having nearly identical shear bond strengths, Groups A (P+AE) and B (AA+AE) did have statistically different ARI scores. This however, did not result in enamel surface damage in the air-abrasion and acid etch group as previously hypothesized. Images obtained from the stereomicroscope and electron scanning microscope reveal no major observational differences in enamel surface topography before or after de-bonding.

Based on this study, the following recommendations and conclusions can be made regarding enamel conditioning prior to bonding:

1. Air-abrasion + acid etch does not result in a tripled SBS.
2. Air-abrasion + acid etch does not harm the enamel surface upon de-bond.
3. The SBS of air-abrasion + acid etch and pumice + acid etch are not significantly different.
4. The SBS of air-abrasion + acid etch and pumice + acid etch with air-abrasion only is significantly different.

5. Group C (AA) had significantly more ARI scores of 0 than Group A (P+AE) and Group B (AA+AE).

Overall, the use of air-abrasion is comparable to that of pumice. Both methods serve to rid the bonding surface of debris prior to acid etching. Either method will result in a clinically acceptable bond; therefore, the choice should be left to the orthodontist regarding which approach to use. Future studies could utilize human teeth, or alter the particle size, pressure, and duration to see if a greater surface roughness is achieved.

The purpose of this study was to see if the combination of air-abrasion and acid etching tripled the shear bond strength, and if so, did it cause damage to the enamel surface when de-bonded. This study concluded that the shear bond strength was not tripled, nor was the enamel surface damaged.

Appendices – Raw Data

Group A	Newton	Mpa	ARI
1	150.67	17.89	1
2	209.18	24.84	0
3	147.12	17.47	2
4	160.3	19.03	1
5	188.37	22.37	0
6	156.55	18.59	1
7	207.36	24.62	2
8	189.32	22.48	0
9	76.8	9.12	1
10	258.86	30.74	2
11	150.3	17.85	0
12	244.37	29.02	0
13	238.37	28.3	0
14	210.57	25	0
15	225.64	26.79	1
16	220.87	26.23	1
17	162.62	19.31	1
18	173.37	20.59	0
19	148.87	17.68	0
20	197.28	23.43	1
21	170.84	20.29	0
22	216.52	25.71	0
23	188.25	22.35	0
24	118.69	14.09	2
25	142.7	16.94	2
26	208.67	24.78	0
27	98.78	11.73	3
28	185.88	22.07	1
29	189.71	22.53	0
30	200.47	23.81	1

Appendix 1. Group A Data.

Group B	Newton	Mpa	ARI
1	174.3	20.7	1
2	220.58	26.19	1
3	91.52	10.87	0
4	190.96	22.67	1
5	122.59	14.56	1
6	222.23	26.39	1
7	154.34	18.33	2
8	124.29	14.76	2
9	213.11	25.31	1
10	220.2	26.15	1
11	210.24	24.96	1
12	308.84	36.67	2
13	181.58	21.56	1
14	238.73	28.35	2
15	119.03	14.13	2
16	162.31	19.27	2
17	218.89	25.99	1
18	183.73	21.82	2
19	164.56	19.54	2
20	253.93	30.15	1
21	223.7	26.56	1
22	34.97	5.23	3
23	0	0	0
24	178.47	21.19	2
25	249.32	29.6	1
26	241.12	28.63	0
27	221.5	26.3	1
28	212.57	25.24	1
29	182.39	21.66	1
30	186.23	22.11	2

Appendix 2. Group B Data.

Group C	Newton	Mpa	ARI
1	67.77	8.05	0
2	58.25	6.92	0
3	88.19	10.47	0
4	85.41	10.14	0
5	90.66	10.77	0
6	100.21	11.9	0
7	48.7	5.78	0
8	60.06	7.13	0
9	68.11	8.09	0
10	91.52	10.87	0
11	80.86	9.6	0
12	87.4	10.38	0
13	64.02	7.6	0
14	52.2	6.2	0
15	19.21	2.28	0
16	102.27	12.14	0
17	20.04	2.38	0
18	75.98	9.02	0
19	22	2.61	0
20	16.04	1.9	0
21	103.68	12.32	0
22	69.01	8.19	0
23	52.6	6.25	0
24	62.68	7.44	1
25	56.01	6.65	0
26	57.49	6.83	0
27	71.32	8.47	0
28	106.01	12.59	0
29	98.81	11.73	0
30	74.44	8.84	0

Appendix 3. Group C Data.

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