

EFFECTS OF REFRIGERANT SPRAY ON ORTHODONTIC COMPOSITE
RESIN-BRACKET DEBOND STRENGTH AND ASSOCIATED
ADHESIVE REMNANT INDEX

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EFFECTS OF REFRIGERANT SPRAY ON ORTHODONTIC COMPOSITE
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ABSTRACT

This study evaluated effects of refrigerant spray and crosshead speed on orthodontic composite resin shear debond strength and Adhesive Remnant Index (ARI) after bond failure. Orthodontic brackets were bonded to forty paired extracted mandibular third molars. Pairs were divided into experimental and control groups, with and without refrigerant spray prior to debond, respectively. Each group was further divided into two subgroups based on crosshead speed of 1 or 10 mm/min. Bracket shear debond strength was tested with a universal testing machine and ARI scores assessed. Results showed no statistically significant difference for shear debond strength or ARI score as a function of refrigerant spray usage. Statistically significant differences were shown for shear debond strength and ARI score as a function of crosshead speed. As crosshead speed increased, shear debond strength and ARI score both increased. These results indicate that application of refrigerant spray prior to bracket debonding is not beneficial.

This abstract of 150 words is approved as to form and content.

APPROVAL PAGE

The faculty listed below, appointed by the Dean of the School of Dentistry, have examined a thesis titled “Effect of Refrigerant Spray on Orthodontic Composite Resin-Bracket Debond Strength and Associated Adhesive Remnant Index” presented by Lauren Ashley Gossett, candidate for the Master of Science in Oral Biology degree, and certify that in their opinion it is worthy of acceptance.

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CHAPTER 1

INTRODUCTION

Bracket Bonding and History

Orthodontics is a specialty of dentistry that treats malocclusions arising from dental or jaw discrepancies. In order to fix malocclusions orthodontists must be able to control the movement of teeth. This is done by placing a band or bracket on the tooth, which acts like a handle to help move teeth into their proper alignment. Each band and bracket has a milled tube or slot of specific dimensions that receives an arch wire transmitting force to the teeth in all three planes of space: buccal/lingual, mesial/distal, and occlusal/gingival. Arch wires of different sizes and material compositions, tooth configurations, and tube/slot constraints cause different forces to be placed on teeth. Orthodontists control the force system that directs teeth into more ideal positions by selecting the sizes, types, and shapes of the wires and mechanics used during treatment. Once the teeth are moved into proper alignment through the use of a series of customizable arch wires, the bands and brackets are removed.

Prior to development of improved bonding materials and brackets, bands were used. The first orthodontic bands were metal strips that were welded together in order to encompass and fit each individual tooth. By the late 1930s, preformed orthodontic bands were available that came in numerous sizes that could be manipulated to fit each tooth. Although orthodontic bands allowed the operator precise control over the movements of teeth, they came with many problems. It was difficult to fit a band on each tooth and extremely time consuming to cement them. It was also difficult to identify the beginning of carious lesions if the band cement was leaking (Wahl 2005). However, the main problem was upon removal of the bands, spaces were left between each tooth (Wahl 2005).

Bands were used exclusively for orthodontic treatment until around 1965. Ten years earlier in 1955, Buonocore determined that better bracket retention was seen with the use of acid etching prior to bonding (Schwartz 1967). However, it was not until 1965 when epoxy resin bonding was brought to the specialty of orthodontics by Newman that direct bonding of orthodontic brackets became a viable alternative to banding teeth (Bishara et al. 2007). Orthodontic brackets allow the orthodontist to retain precise control of tooth movements, without the problems encountered with bands. There was no longer the difficulty of having to deal with spaces upon removal of the appliances, the brackets were easier to place, they were more esthetic and hygienic, and they were less irritating to the gingiva (Proffit et al. 2007). However, a new drawback became apparent when frequent orthodontic bracket failures occurred. Many of the adhesives used in orthodontics were originally created for use as dental restorative materials (Wahl 2005). Therefore, the molecular composition of composite adhesives needed to be altered to fit better their use in the field of orthodontics. Restorative dentistry strives to obtain the highest bond strength possible between composite resin and tooth structure, but that is not the case with orthodontic adhesives. Orthodontic adhesives need to provide strong enough bonds to retain brackets on teeth during the transmission of forces from the orthodontic arch wires to the teeth, but weak enough to allow the orthodontist to remove the brackets without enamel damage and allow for easy clean-up of the tooth surface when the treatment is finished (Brantley and Eliades 2001).

Bracket Adhesives

There are three basic orthodontic adhesives used and these can be divided according to their setting reactions: free-radical/addition reactions (e.g. resin composite), acid-base

reactions (e.g. glass ionomers), and hybrid acid-base/free-radical reactions (e.g. resin-modified glass ionomers) (Hervas-Garcia et al. 2006).

Glass ionomers were introduced in 1972. They are mainly used for bonding bands rather than brackets to tooth structure. They have the additional ability of fluoride release which is beneficial in preventing demineralization and have a chemical bond to the tooth structure (Kent et al. 1973; Shapiro 1974). However, glass ionomers have been shown to have significantly lower bond strengths compared to resin composite adhesives and are therefore not commonly used as an orthodontic bonding adhesive for brackets (Schwartz 1967).

The addition of resin to glass ionomers formed what are called resin-modified glass ionomers (RMGI) (Bishara et al. 2007). RMGI also release fluoride like their parent compounds, but have the added benefit of higher bond strengths (Forsten 1995). However, RMGI still have lower bond strengths compared to resin composite adhesives (Komori and Ishikawa 1997; Summers et al. 2004). Because of this, resin composite adhesives are the most commonly used in orthodontic treatment today (Kent et al. 1973).

Resin Composite Adhesives

Resin composite adhesives (referred to as adhesives from now on) contain three major components: organic polymer matrix, inorganic filler particles, and a coupling agent.

The organic polymer matrix is made up of mono-, di-, or tri-functional monomers, a free radical polymerization initiation system, an accelerator, a stabilizer or inhibitor, and an ultraviolet light absorber. The functional monomers are the backbone of the composite resin system, bisphenol A glycidyl dimethacrylate (Bis-GMA) being the most commonly used (Hervas-Garcia et al. 2006). The free radical polymerization initiation system determines the

type of setting reaction. There are three types of setting reactions: chemical, light, and dual activation.

The first orthodontic bonding adhesives used were chemical-cured two-paste systems. A base and catalyst were mixed together and used to attach the bracket to the tooth. Although these chemical-cured composites performed the job of attaching brackets to the tooth, they had many downsides. These included poor color stability, unpredictable setting time, and incorporated porosities while mixing (Hervas-Garcia et al. 2006). Nowadays, orthodontic adhesives are light-cured and have almost made the use of chemical-cured composites obsolete.

Light activation is the most commonly used due to operator control of working time (Lutz and Phillips 1983), shorter setting time (Hervas-Garcia et al. 2006), more predictable setting, less technique sensitivity (Brantley and Eliades 2001), higher initial bond strength (Eliades 2006), less mixing-incorporated porosities (Ewoldsen and Demke 2001), and easy removal of excess bonding material. The accelerator acts on the initiator allowing curing to take place in a clinically acceptable time period. The stabilizer or inhibitor maximizes the product's storage life prior to curing and its chemical stability after curing. The ultraviolet wavelength absorbers provide color stability and eliminate the effects of ultraviolet light on the amine compounds in the initiator system (Hervas-Garcia et al. 2006).

The last two components are inorganic filler particles and a coupling agent. The inorganic filler determines the physical and mechanical properties of the composite. It reduces the thermal expansion coefficient and overall curing shrinkage, improves handling and esthetic result (Hervas-Garcia et al. 2006). The coupling agent is a molecule with a

silane group at one end and a methacrylate group at the other end that bonds the filler to the resin matrix.

Bonding Protocol

The bonding protocol for orthodontic brackets has evolved over the past few decades. Often the first step performed was cleaning the tooth surface with fluoride-free pumice to remove the dental pellicle and plaque. However, pumicing the tooth prior to bonding has not been shown to improve the bond strength when using etchant and primer, and has not remained part of the normal bonding procedure (Ireland and Sherriff 2002). Therefore, the first step is etching the tooth surface with 37% phosphoric acid for 15-30 s. This removes a small amount of soft interprismatic enamel and opens up pores between the enamel prisms so the adhesive can penetrate into the enamel surface to create a mechanical bond (Burgess et al. 2006). The etchant is rinsed away with water and air-dried until a frosted appearance can be seen (Burgess et al. 2006). This is followed by application of a hydrophilic unfilled resin primer that flows into the etched enamel. The desire to decrease the number of steps involved in orthodontic bonding has led to the development of self-etching primers. In place of phosphoric acid and hydrophilic unfilled resin primers, a self-etching primer can be used which eliminates one step in the bonding process. The adhesive is then applied to the bracket base and the bracket is placed on the tooth. The excess adhesive is removed from the periphery of the bracket. The adhesive is light-cured with a blue light (400-470 nm) directed at the gingival surface for 10 seconds (s) and the occlusal surface for 10 s (Burgess et al. 2006).

Strength of Bond between Enamel and Bracket and In Vivo Bracket Debonding

Premature bond failures are problematic when trying to treat orthodontic patients. They result in increased treatment time, number of patient visits, material costs, personnel time, and doctor chair time (Brantley and Eliades 2001). Some authors state that bond strength values between 6-8 MPa are adequate for clinical situations to resist forces present during orthodontic movement of teeth (Bennett et al. 1984; Meehan et al. 1999). These values of 6-8 MPa, originally cited as 60-80 kg/cm², stem from a 1975 article that reviewed materials and procedures used for direct bracket bonding, but are based only on the author's speculative opinion regarding clinically acceptable bond values (Reynolds 1975). However, other studies have tested debond strengths both in vivo and in vitro and have exhibited a large range of debond strengths from 2.8-10 MPa to be clinically acceptable (Hajrassie and Khier 2007; Lopez 1980; Murray and Hobson 2003; Reicheneder et al. 2009). Within this range of values, it is predicted that orthodontic brackets will remain attached to teeth during treatment without prematurely debonding. However, if debond strengths are greater than 10 MPa, then enamel damage can occur during orthodontic bracket debonding (Retief 1974; Nkenke et al. 1997). While there is a large range of clinically acceptable bond strength measurements reported in the literature, there are no studies currently available that determine the exact minimum bond strength needed to resist bracket debonding with the application of orthodontic or other ordinary functional forces.

It is also difficult to find related data that could help infer minimum bond strengths needed to resist debonding during tooth movement. That is, besides optimal applied forces for tooth movement not being unequivocally known, the areas over which forces are applied have not usually been measured and need to be considered in assessing optimal minimum

bond strengths. Ren and co-workers (Ren et al. 2003) performed a comprehensive systematic review of orthodontic literature that resulted in identification of over 400 published articles dealing with the optimum force magnitudes for orthodontic tooth movement. Out of all the papers reviewed, 305 used human subjects, and only 12 of those met inclusion criteria. Studies were excluded if they had any of the following: no quantification of orthodontic force magnitude, no quantification of rate or amount of tooth movement, no control group or split-mouth design, number of experimental sites per group less than or equal to 5, use of extraoral or functional appliances, observation period less than or equal to 1 week, and medication and surgical or physical intervention other than orthodontics in experimental design. These 12 studies examined the initial force levels required for tooth movement. These force levels covered a wide range of values for molar tipping (100-500 cN), incisor tipping (50-200 cN), and canine retraction (18-1500 cN). Since there are a wide variety of clinical force levels for retracting and tipping teeth, it is difficult to determine clinically acceptable bond strength measurements as well.

In Vivo Bracket Debonding

Debonding of orthodontic brackets is an inevitable situation in orthodontic treatment. Once the teeth have been moved into more ideal locations and the occlusion is acceptable, the brackets are removed. Numerous techniques have been developed to try to minimize patient sensitivity and enamel damage during the debonding procedure. Diedrich (Diedrich 1981) estimated that 150-160 μm of enamel could be lost during bracket removal. Enamel damage is of clinical importance because the concentration of fluoride is greatest at the surface of enamel (Retief and Sadowsky 1975). If this layer of enamel is removed during bracket debonding, then the tooth surface will be more susceptible to demineralization.

Bishara and co-authors (Bishara et al. 1995) showed that excessive debonding stresses/pressures (>11.1 MPa) caused enamel cracks which were less probable when debonding stresses were lower (7.1 MPa).

The location of bond failure is also of importance when it comes to enamel damage. There are four possible locations for bond failure: bracket-adhesive interface, within the adhesive, tooth-adhesive interface, within the tooth. The site of bond failure will determine the level of enamel damage incurred. According to Olsen and others (Olsen et al. 1997) a bond failure at the bracket-adhesive interface will have the least probability of causing enamel damage. However, accompanying the decreased probability of enamel damage is an increase in chair side time required to clean remaining adhesive from tooth surfaces (Chen et al. 2007). Fox and co-authors (Fox et al. 1994) stated that the ideal location for debonding in orthodontics is at the tooth-adhesive interface. This would make the debonding process simpler and polishing of the enamel surface easier. However, if the bond failure site is at the tooth-adhesive interface, the risk of enamel fracture is increased (Odegaard and Segner 1988). When the bonding procedure is performed, the etchant removes approximately 10-20 μm of surface enamel (Brantley and Eliades 2001). This etched enamel becomes porous and allows the adhesive to flow into the enamel and create a mechanical interlocking bond. These adhesive resin tags will remain attached to the porous surface enamel and during removal can detach areas of the surface enamel if the location of debonding is between the adhesive and tooth structure.

The Adhesive Remnant Index (ARI) is a scale which classifies location of bond failure. This index appraises the amount of adhesive remaining on the tooth and bracket and is divided into 4 scoring groups: score 0: no adhesive left on tooth, score 1: less than half of

the adhesive left on the tooth, score 2: more than half of the adhesive left on the tooth, and score 3: all adhesive left on the tooth, with distinct impression of the bracket mesh (Artun and Bergland 1984). This scoring system was first introduced by Artun and Bergland in 1984 (Artun and Bergland 1984). They stated that although one might argue its use is largely subjective, the scoring system is of great value and is similar to other scoring systems used in other studies (Zachrisson and Arthun 1979; Artun and Bergland 1984). Other investigators have proposed a modified ARI system in which 6 scoring groups are used with the cut-offs of 25%, 50% and 75% or 5 scoring groups with the cutoffs of 10% and 90% (Chen et al. 2007; Bishara et al. 2008). However, these modified systems have not proven to be clinically or statistically more relevant and have not been used more often when determining the remaining adhesive on the tooth surface. From 1996 through November 2010, the article by Artun and Bergland describing the ARI scoring system has been cited 265 times.

Factors Affecting Debond Strength and Measurement Techniques

In Vivo

The bonding procedure used when attaching orthodontic brackets to the teeth of patients is technique sensitive. The most frequent cause of premature bond failure is moisture contamination during the bonding process arising from gingival crevicular fluids, saliva, or water (Ewoldsen and Demke 2001). If there is any moisture contamination during the bonding process, the procedure must be started over from the beginning and the tooth must be acid-etched and primed again before attempting to bond the orthodontic bracket. Other issues that can affect the bond strength of attached brackets are etching time (Surmont et al. 1992), type of etchant and primer used (Bishara et al. 2008), adhesive system used

(Katona and Long 2006), curing light source (Sfondrini et al. 2004), distance from light tip to adhesive layer (Sfondrini et al. 2006), and bracket base design (Sharma-Sayal et al. 2003).

Debonding forces for brackets in the past were reported in Newtons (N). However, this value does not take into account the area of the bonded interface. Therefore, these values are often misleading (Brantley and Eliades 2001). Nowadays, debond strength measurements are reported in pascals, specifically megapascals (MPa), which are units of pressure or stress. That is, the force of debonding divided by the area of the bracket base. These values provide measurements of debond strengths that are comparable between studies because the area of force application is taken into account.

Some studies have been performed that use a fabricated intraoral debonding device with attached force gauge to help compare debond strengths in vitro and in vivo. For example, Pickett et al. (Pickett et al. 2001) compared in vitro and in vivo debonding forces using the same intraoral debonding device and found these forces were on average 12.82 MPa and 5.47 MPa, respectively. They also tested brackets bonded to teeth in vitro using a universal testing machine with shear force application and found a mean debond strength of 11.02 MPa. Both the in vitro use of the intraoral debonding device and the universal testing machine shear force had significantly higher debond strengths than actual in vivo measurements.

Murray and Hobson (Murray and Hobson 2003) performed an in vivo experiment in which subjects wore a removable appliance with brackets bonded to enamel slabs. However, the debond strengths were measured ex vivo after 4, 8, and 12 weeks of exposure to the oral cavity and compared with debond strengths of an in vitro control group. The debond strengths of the in vitro group were higher than the in vivo group for all time intervals. For

the in vitro group, the debond strengths were 9.04, 8.34, 6.35 MPa and for the in vivo group they were 6.14, 3.54, and 3.73 MPa for the 4, 8, and 12 week time intervals respectively. Although this study allowed the brackets to be exposed to the oral cavity, the study failed to test the debond strength in the oral cavity.

The study performed by Hajrassie and Khier (Hajrassie and Khier 2007) compared debond strengths in vivo and in vitro using the same digital force gauge during debonding directly in the mouth and on the bench top. They also tested debond strengths at 4 different time periods following bonding: 10 minutes (mins), 24 hours (hrs), 1 week, and 4 weeks. For the in vitro group they used a universal testing machine and debonded the brackets with a shear force provided by a metal plier tip attached to the digital force gauge. The same force gauge and metal plier tip were used to debond brackets in vivo. The mean debond strengths for the in vivo group for 10 mins, 24 hrs, 1 week, and 4 weeks were as follows: 5.24, 6.01, 5.49, 5.92 MPa. The mean debond strengths for the in vitro group for 10 mins, 24 hrs, 1 week, and 4 weeks were as follows: 12.70, 14.22, 14.32, 14.66 MPa. Overall, the debond strengths for the in vivo group were significantly lower than the debond strengths for the in vitro group at all time intervals. It was also shown that the lowest debond strengths for both the in vitro and in vivo groups were recorded 10 mins after bracket bonding. The debond strengths were comparable for the 24 hour, 1 week, and 4 weeks time interval groups within each of the in vitro and in vivo groups.

It is difficult to standardize conditions in vivo when trying to test bonding and debonding procedures. Nevertheless, as demonstrated by the previous studies, average debond strengths measured in vivo were up to approximately 6 MPa and were significantly lower compared to debond strengths measured in vitro.

In Vitro

As described above, in vivo measurement of debond strength is challenging; therefore, many experiments have been performed in vitro and the results generalized to in vivo scenarios. However, one of the most difficult problems in trying to generalize testing results from in vitro studies to clinical situations is that the complex interaction of biological processes that occur in the oral cavity cannot be completely reproduced in vitro (Eliades et al. 1999). Another major problem in assessing in vitro debond strength is the lack of standardization of methodology. There are numerous variables that, if altered, can change the debond strengths. Many authors have proposed and emphasized the need for standardization of the methodology in order to make accurate comparisons between debond strengths from different studies (Soderholm 1991; Fox et al. 1994; Stanford et al. 1997). The variables that need to be controlled and standardized are the following: type of bracket tested, type of adhesive used (Egan et al. 1996), polymerization time (Evans et al. 2002), testing device used for debonding (Fowler et al. 1992; Sinhoreti et al. 2001), location of force applied to bracket (Katona 1994; Klocke and Kahl-Nieke 2005b), type of loading used (Prietsch et al. 2007), crosshead speed (Klocke and Kahl-Nieke 2005a), type of tooth tested (Hobson et al. 2001), testing conditions (temperature and humidity) (Plasmans et al. 1994), number of specimens used per test (Beech et al. 1985), and time between bonding and debonding (McCourt et al. 1991).

Most in vitro debond strength studies are performed with the use of a universal testing machine. This machine applies increasing force magnitudes in a predetermined mode and quantifies the force as the bond fails. Bond failure is also known as “debonding”. The two most commonly tested loading modes for debonding are shear and tensile. Shear forces

cause a sliding dislocation of one side of the bracket base with respect to the opposite side. Tensile forces cause a pulling force in the direction of load application to the bracket base. Although there have been requests from the research community to standardize the methodology of debonding, nothing has been agreed upon (Fox et al. 1994; Stanford et al. 1997).

A study by McCourt et al. (Mccourt et al. 1991) compared the debond strengths of orthodontic brackets 24 hrs and 30 days following bonding. They bonded brackets to extracted human teeth and performed shear testing on a universal testing machine. They found no significant difference between the debond strengths at 24 hrs (11.35 MPa) and 30 days (10.80 MPa). It has been shown that the debond strengths of adhesives increase after curing for up to 24 hrs. This is due to further polymerization of the adhesive components and additional maturation time to allow the adhesive to reach its optimal strength (Yamamoto et al. 2006).

Reicheneder and colleagues (Reicheneder et al. 2009) compared the shear and tensile debond strengths of 8 different orthodontic adhesives using a universal testing machine. All adhesives except for Fuji Ortho LC®, Transbond LR®, and Light Bond® had lower debond strengths under tensile testing than shear testing. The debond strengths for Transbond LR® were 6.78 MPa for tensile and 5.47 MPa for shear. Even though the debond strengths differed between shear and tensile testing, the results were not clinically significant. These debond strength results were lower than those seen with other in vitro studies. In this study, brackets were bonded to bovine teeth and not extracted human teeth. Oesterle and co-authors (Oesterle et al. 1998) determined that lower debond strengths are seen when bovine teeth are used instead of human teeth.

Sunna and Rock (Sunna and Rock 1999) performed a study to determine if debond strengths differed between Adhesive PreCoated (APC) brackets, where a layer of adhesive is applied to the bracket by the manufacturer versus non-APC brackets, where the adhesive is applied by the operator just prior to bonding. One APC bracket system and two non-APC bracket systems were used, all utilizing the same adhesive (Transbond XT®). The non-APC bracket adhesive was cured for 20 s, while the APC bracket adhesive was cured for 10, 20, and 40 s. When the non-APC brackets were debonded using tensile testing, the debond strength for one type of bracket (Dyna-Lock) was 22.32 MPa and for the other (Straight Wire) was 21.56 MPa. The APC bracket debond strength differed depending on the curing time. The debond strengths were 17.33, 17.82, and 22.08 MPa for the 10, 20, and 40 s curing times respectively.

A few studies have attempted to mount a debonding plier on a universal testing machine to simulate better the debonding force that occurs intraorally. Habibi and co-workers (Habibi et al. 2007) performed a study where a custom-made jig stabilized a debonding plier. The debonding plier was placed at the mesiodistal bracket-tooth interface and forces were applied to both beaks of the plier with a universal testing machine. This produced a bilateral force on the specimen, whereas the conventional universal tester experiments apply a shear or tensile force only unilaterally to the specimen. The mean debond strengths obtained by Habibi and co-workers with the bilateral force technique for the metal and ceramic brackets were 20.73 and 13.87 MPa, respectively. Although this technique can be utilized in vitro to determine debond strengths, it requires a significant preload on the specimen prior to debonding. The device used by Habibi and co-workers had a custom-made jig to hold the plier stable but this set-up is not easily reproduced at this time.

That is, the methodology was not standardized and this makes comparison of results with other debonding studies difficult.

Bishara and colleagues (Bishara et al. 1995) also used a debonding plier positioned on a universal testing machine to debond ceramic brackets. However, unlike the article by Habibi and co-workers (Habibi et al. 2007), the debonding plier was not supported by a custom-made jig. Instead, the debonding plier was free-standing with force being applied only on the beaks of the plier with the handles left unsupported. This set-up appears unstable and does not mimic the use of a debonding plier clinically where the force is applied to the handles and not the beaks. The debond strengths calculated in the Bishara et al. study ranged from 6.6-10.1 MPa, depending upon the type of ceramic bracket tested.

Crosshead Speed

As previously stated, one variable which must be controlled during testing is the crosshead speed. This is the speed at which the crosshead of the universal testing machine moves during testing and this speed must be set by the researcher. In a study performed by Lindemuth and Hagge (Lindemuth and Hagge 2000) they theorized that composite may act like a viscous material at slow crosshead speeds and a brittle material at fast crosshead speeds. They tested the shear debond strength of enamel and dentin at crosshead speeds of 0.1, 0.5, 1.0, 5.0, and 10.0 mm/min. The shear debond strengths of enamel were not significantly different for the crosshead speeds of 0.1-5.0 mm/min and ranged from 15.39-16.77 MPa. However, the shear debond strength of enamel at the 10.0 mm/min crosshead speed was significantly lower at a value of 13.80 MPa. Klocke and Kahl-Nieke (Klocke and Kahl-Nieke 2005a) performed a similar study to investigate this theory; they also found no significant differences in debonding forces with varying crosshead speeds of 0.1-5.0

mm/min. Unlike Lindemuth and Hagge (Lindemuth and Hagge 2000), Klocke and Kahl Nieke (Klocke and Kahl-Nieke 2005a) did not test a group at 10.0 mm/min. They tested 4 groups of 30 bovine teeth with crosshead speeds of 0.1, 0.5, 1.0, and 5.0 mm/min. The mean debond strengths for the 4 different crossheads speeds listed in increasing order were 215.35, 231.79, 236.64, and 224.95 N. Their results indicate that crosshead speeds of 0.1 to 5.0 mm/min do not affect the viscoelastic and brittle properties of the composite or the type of bond failure that occurs.

Eliades and colleagues used an increased crosshead speed of 200 mm/min in a study which used two groups of 20 human teeth with metal brackets bonded to the enamel surface (Eliades et al. 2004). They used crosshead speeds of 1 mm/min and 200 mm/min which represented the standard debond speed and the approximate jaw velocity during chewing, respectively. For the 1 mm/min group the debond strength was 66.4 N and for the 200 mm/min group the debond strength was 26.19 N. This study showed significant differences between crosshead speeds and debond strengths. This pattern of decreased debond strength with increased crosshead speed is thought to be due to the stiff body response of the composite resin and the elimination of its viscoelastic properties at higher speeds. Conversely, when a slow crosshead speed is used, the composite resin has the ability to absorb some of the energy through elastic deformation and this may result in higher debond strengths.

The article by Bishara et al. (Bishara et al. 2005) also showed a decrease in debond strength with increased crosshead speed. They tested two groups of 20 human teeth at crosshead speeds of 0.5 and 5.0 mm/min. For the 0.5 mm/min group the debond strength was 12.2 ± 4.0 MPa and for the 5.0 mm/min group the debond strength was 7.0 ± 4.6 MPa.

Although it is difficult to compare these results with those of Klocke and Kahl-Nieke (Klocke and Kahl-Nieke 2005a), since in the latter study mean debond strengths were reported in Newtons and bracket base area was not stated, the results can be compared to those of Lindemuth and Hagge (Lindemuth and Hagge 2000). Both studies show similar patterns with a decrease in debond strength with increase in crosshead speed.

Finnema et al. (Finnema et al. 2010) performed a systematic review to look at what experimental variables affect bond strength testing. They reviewed the results of 24 studies and looked at 27 experimental conditions, identifying three that significantly affected in vitro debond strength testing: storage medium used after bonding, photopolymerization time, and crosshead speed. There was considerable diversity of the materials and methods of all the articles included in the systematic review. All of the 24 studies had a crosshead speed between 0.1-5.0 mm/min with a median of 0.5 mm/min and an interquartile range of 0.5-1.0 mm/min. Twenty-three percent of the studies used a wire loop to debond the brackets while the remaining 77 percent used a shearing blade to debond the brackets. Even after predictor variables were accounted for, significant heterogeneity between the studies included in the systematic review existed. Based on the diversity in reported test conditions, they determined on average, when the crosshead speed was increased by 1 mm/min, the debond strength increased by 1.3 MPa. This is a different pattern from the previous studies on crosshead speed.

Techniques for Bracket Removal

Mechanical Debonding

The most common means of debonding orthodontic brackets in vivo is with a bracket debonding plier. These pliers apply a force across the bracket base which deforms the

bracket base and causes the bond to fail, normally between the bracket-adhesive interface (Brosh et al. 2005). The beaks of the plier can be placed either at the adhesive layer between the bracket and tooth (base method) or between the bracket base and tie-wings (wing method). Although the base method requires 1.5 times more debonding force according to an in vitro study, there is no significant difference in location of bond failure (Bennett et al. 1984). Mechanical debonding with a bracket debonding plier has been shown to be the safest and most cost effective debonding method, but does not normally permit recycling of the bracket due to distortion of the base and slot (Bennett et al. 1984). There have also been concerns that the beaks of the debonding pliers could cause enamel damage (Oliver 1988). The force required to debond a bracket with debonding pliers often causes tooth sensitivity and discomfort to the patient (Tsuruoka et al. 2007). These forces are transmitted to teeth that are often still mobile following orthodontic treatment and are very sensitive to pressure (Bishara et al. 1995). The mechanical debonding method often produces sudden failure of the bond which can cause loss of control of the pliers and injury to adjacent soft tissue (Bishara et al. 1995).

Ultrasonic Debonding

Brackets can also be removed with the use of an ultrasonic device, which erodes the adhesive between the enamel and bracket base helping to facilitate bracket removal (Krell et al. 1993). Ultrasonic debonding causes separation at the tooth-adhesive interface, tending to cause more enamel damage; however the likelihood of enamel damage with the use of ultrasonic debonding is minimal due to the low force levels (<1 MPa) required to cause bond failure (Krell et al. 1993). Boyer et al. (Boyer et al. 1995) compared the debond strength of orthodontic brackets with shear force on a universal testing machine and an ultrasonic device.

The amount of force required to debond the bracket with the shear testing ranged from 7.4-11.4 MPa while the force for the ultrasonic ranged from 0.15-0.34 MPa. Although the force required to debond the bracket is low, the frequency of vibrations (up to 30,000 strokes/s) can create increased discomfort with sensitive teeth (Bishara and Trulove 1990b). The same ultrasonic tip used to debond the bracket can also be used to clean-up residual adhesive (Bishara and Trulove 1990b). Although ultrasonic debonding has a low incidence of enamel damage, it is not commonly used as a method to debond brackets because of the increased time required to debond, the significant wear on the ultrasonic tip, and the high costs associated with replacing the ultrasonic tips (Bishara et al. 1994). It also has the potential of creating soft tissue injury and pulpal damage if adequate water spray is not used to reduce heat build-up (Bishara and Trulove 1990b).

Effect of Heating Polymers

Researchers have attempted to debond brackets by heating the composite resin to decrease its viscosity. The two main forms of heat-induced debonding are electrothermal and laser debonding. When polymer-based composite materials are heated their structural properties are altered. Polymers have a glass transition stage in which the physical property of the polymer goes from a rigid solid to a viscous solid (Rueggeberg et al. 1992). For example, the glass transition for Bis-GMA/HEMA composite resins is around 103-159 °C depending upon the photoinitiator and water content (Park et al. 2009). So at temperatures below this range, this type of polymer is a rigid solid and the chains that make up the polymer unit are locked in place (Park et al. 2009). When the temperature is above the glass transition certain chains within the polymer gain kinetic energy and begin to vibrate, weakening van der Waals forces that hold the polymer together (Rueggeberg et al. 1992).

These chains begin to break apart due to the vibrations and individual chains start to move independently (Abreu et al. 2007). This is what causes the decreased viscosity of the polymer when it is subjected to heat (Walter et al. 2009).

Electrothermal Debonding

Electrothermal debonding helps remove brackets with the use of a heating device that is placed in the bracket slot and engages the bracket tie-wings. The heating element is warmed (reaching approximately 450°F) and transfers heat to the bracket softening the underlying adhesive allowing the bracket to be easily removed from the tooth surface (Bishara and Trulove 1990a; Zarrinnia et al. 1995). In a study performed by Crooks et al. (Crooks et al. 1997) they measured the temperature of the electrothermal debonding blade, the buccal surface of enamel directly below the heated bracket, and the pulpal wall at the time of bond failure. With a thin layer of resin (Transbond®, <0.5 mm) and 0 Nmm of torsional debonding force, the blade's mean temperature was 385.49 °C. The mean temperature for the buccal surface of the tooth increased by a value 103.82 °C, and the pulpal wall by a value of 15.15 °C. When 40 Nmm of torsional force was added, the mean temperature of the blade was 408.98 °C, while buccal surface and pulpal wall temperatures increased by 54.35 °C, and 4.74 °C, respectively. When the torsional force was increased to 80 Nmm, the mean temperature of the blade was 505.31 °C, while buccal surface and pulpal wall temperatures increased by 44.94 °C, and 2.72 °C, respectively. In order to add a torsional force to the electrothermal blade, a custom-made torsional device was attached to the blade. The heating cycle was activated first and then the torsional force was applied. This is why the blade temperature increased as the torsional force increased. However,

overall the highest temperature increase at the pulpal wall was evident with 0 Nmm torsional force while the lowest was seen with 80 Nmm torsional force.

The electrothermal debonding technique is less traumatic to the underlying enamel and has shown less enamel damage due to a debond location occurring at the bracket-adhesive interface. It is thought that because the thermal expansion properties of the adhesive differ from that of the bracket, the contraction and expansion that occur at the bracket-adhesive interface help to weaken the bond (Bishara and Trulove 1990b). One study found that subject discomfort was decreased with the use of electrothermal debonding when compared to mechanical debonding (Kraut et al. 1991). However, soft tissue burns and adverse pulpal tissue damage may result if this technique is not correctly administered (Bishara and Trulove 1990a). Kraut et al. (Kraut et al. 1991) looked at the pulpal response of human teeth that were extracted for orthodontic purposes after ceramic brackets were debonded with either an electrothermal debonding device or orthodontic pliers. They found that there was no evidence of pulpal necrosis or inflammatory response two weeks following electrothermal debonding of ceramic brackets. However, Jost-Brinkmann and others (Jost-Brinkmann et al. 1992) also performed a study on human teeth scheduled for extraction for orthodontic purposes. Brackets were debonded using either the electrothermal debonding technique or mechanical debonding with orthodontic pliers and then extracted 24 hrs later. When the teeth were histologically examined, they found localized pulpal damage after electrothermal debonding was performed when more than one heating cycle was required to debond brackets successfully.

Laser Debonding

Laser debonding has also been evaluated as an alternative to mechanical debonding. Laser debonding can break down the adhesive by one of three methods: thermal softening, thermal ablation, and photoablation. Thermal softening results in the bracket sliding off the tooth when the laser heats up the adhesive until it softens. This is a relatively slow process and can cause an increase in both tooth and bracket temperatures. Thermal ablation still debonds the bracket by thermal softening, but the heating is so fast that the rise in temperature of the adhesive causes it to go into its vaporization range. This causes the bracket to release from the tooth surface. Photoablation occurs when the laser interacts with the adhesive and the energy levels of the bonds between adhesive atoms rise rapidly above dissociation energy levels, which causes the adhesive to decompose. Both thermal ablation and photoablation proceed very rapidly and therefore allow for very little heat diffusion to the tooth and bracket keeping them around physiologic temperatures (Tocchio et al. 1993).

Abdel-Kader and Ibrahim (Abdel-Kader and Ibrahim 1999) used a CO₂ laser at a power of 50 watts at 1060-nm wavelength to debond 10 ceramic brackets on human premolars extracted for orthodontic purposes. They measured the temperature of the bracket, the enamel directly below the bracket, and the pulpal wall. They found that the temperature of the bracket increased to 93.63 °C, the enamel directly below the bracket increased to 23.13 °C, but the pulpal temperature increase did not exceed 0.7 °C.

Tocchio et al. (Tocchio et al. 1993) debonded both monocrystalline and polycrystalline ceramic brackets with a laser. When trying to debond monocrystalline ceramic brackets there was no differentiation between thermal ablation and photoablation at all power densities for the 248-nm wavelength laser. However, the debonding of

polycrystalline ceramic brackets occurred only by thermal softening. This is contrary to the results found by Strobl and co-authors (Strobl et al. 1992). They tested both monocrystalline and polycrystalline ceramic brackets and determined that debonding occurred by thermal softening of the adhesive.

The advantage of using a laser to help debond brackets is the decrease in debonding time (Mimura et al. 1995). Obata and co-authors (Obata et al. 1999) found that the super-pulse CO₂ laser (laser which produces high energy pulses over a short time period) took less time to debond brackets than a normal-pulse laser (laser with continuous waves of millisecond-duration pulses). However, just like with electrothermal debonding, the heat produced by laser debonding can have adverse effects on the pulpal tissue. Ma and others (Ma et al. 1997) reported a linear relationship between the amount of time the laser was on the tooth and the increase in pulpal temperature. Their data also showed that 8 out of the 10 specimens tested with tensile loading debonded at 1.48 MPa. The biggest downside to laser debonding is the significant cost related to purchasing the laser apparatus and the possibility of soft tissue injury (Brantley and Eliades 2001). Also lasers should not be used on patients with composite restorations as the laser will selectively remove more composite material compared to enamel requiring the composite restoration be replaced (Alexander et al. 2002).

Debonding Brackets with Cooling Mechanisms and Effect of Cooling Polymers

When subjected to cold temperatures, polymer-based composites have an increased modulus of elasticity or stiffness (Nordin et al. 2010). The material undergoes resin hardening due to a reduction in temperature and the composite matrix becomes brittle (Nordin et al. 2010). When a force is applied the formation of microcracks occur creating stress sites that allow the material to fail easily. At low temperatures (-35 °C) when an

elevated strain level is applied to the material, the modulus of elasticity increases causing the material to become more brittle (Nordin et al. 2010).

The main testing of composite material properties performed at extremely cold temperatures has been carried out by structural engineers. Engineers test composite reinforced concrete structures at subzero temperatures to determine how the properties of composites might influence concrete structures such as bridges and roadways in cold climates. These composite reinforced structures have shown an increase in failure after being subjected to temperatures of $-17.8\text{ }^{\circ}\text{C}$ (Karbhari and Eckel II 1994). These specimens tend to fail more readily because of brittle-ductile transition due to increased composite resin brittleness at these extremely cold temperatures (Karbhari and Eckel II 1994). Nordin and co-authors found that fiber-reinforced polymer composite bridge decks have an increase in failure at lower temperatures ($-35\text{ }^{\circ}\text{C}$) because of the brittle nature of composites (Nordin et al. 2010).

Refrigerant Spray as a Cooling Mechanism Prior to Bracket Debonding

No studies have been performed to test the effects of cooling mechanisms on the debonding of brackets. It is thought that when the bracket and adhesive interface is cooled, the adhesive modulus of elasticity will increase and microcracks will form within the composite structure. When a force is applied to debond the bracket, a brittle fracture will occur and be propagated along the microcracks, allowing the bracket to debond easily without damage to the underlying enamel. A possible cooling mechanism that could be used prior to bracket debonding is Endo Ice® (Coltene/Whaledent 2007), also known as refrigerant spray.

Refrigerant spray is an aerosol that is non-flammable and environmentally safe (Coltene/Whaledent 2007). It has a low potential for acute and chronic toxicities and for skin and eye irritations (Dekant 1996). The compound is readily biotransformed within the body by cytochrome P450 into metabolites excreted in the urine (Dekant 1996). When tested on rodents using very high concentrations of 50,000 ppm of 1,1,1,2-tetrafluoroethane for 6 hrs/day for 5 days/week, chronic adverse effects on the liver and testes, such as tumor formation, were seen (Dekant 1996). However, the chronic toxicity is unlikely to be of relevance for humans who are exposed during application of this refrigerant spray because the dosage levels and exposure time are minimal (Dekant 1996).

Endo Ice®, a type of refrigerant spray used in dentistry, has a temperature of -26.2 °C, colder than the normal intraoral temperature range of 0 – 67 °C (Palmer et al. 1992; Linsuwanont et al. 2008). This compound is used in dentistry for the purpose of pulp vitality testing. Rickoff et al. (Rickoff et al. 1988) demonstrated in vivo that the use of thermal vitality tests caused no pathological changes to occur in the pulp. The study looked at 32 premolars that were going to be extracted for orthodontic purposes. Heated gutta-percha (76°C) and CO₂ snow (-76°C) were placed on the facial surface of teeth prior to extraction. The thermal testing device was kept in contact for anywhere from 5 s to 5 mins. Teeth were then extracted and examined histologically. All of the tested teeth had structurally intact pulps with no pathological alterations. During continuous application of the CO₂ snow for 5 mins, the intrapulpal temperature dropped to 9.5 °C after approximately 75 s and then began to return to baseline. An in vivo study conducted by Jones and others (Jones et al. 2002) on 15 human teeth determined that refrigerant spray was more likely to produce a pulpal response in a shorter time period than CO₂ dry ice, even though both agents were effective in

eliciting a pulpal response. This effect is thought to be due to the amount of cold per surface area of the two application methods. The CO₂ dry ice was delivered in a 3.5 mm ice stick while the refrigerant spray was delivered on a #2 cotton pellet (approximately 2 mm in diameter). Although the refrigerant spray elicited a quicker pulpal response that was statistically significant, the results are not considered clinically significant. The overall difference between mean pulpal response times for CO₂ dry ice and the refrigerant spray was only 1-3 s.

Jones (Jones 1999) also showed that the type of carrier used to apply the refrigerant spray will also affect the results of thermal tests. He compared four different carriers (#2 cotton pellet, #4 cotton pellet, wood handle cotton-tip applicator, and cotton rolls) to determine which one was most effective in delivering refrigerant spray to the teeth. A k-type thermocouple was placed against the pulpal wall of an extracted human tooth and the temperature was recorded 10 s after the carrier was placed on the facial surface. When the refrigerant spray was applied to each carrier, the #2 cotton pellet retained the cold temperature for the longest period of time and was considered the most effective delivery system. The mean change in temperature of the pulpal wall 10 s after application of refrigerant spray for the #2 cotton pellet was 47.1 °C whereas the second best mean change in temperature was 5.8 °C for the cotton roll. The #2 cotton pellet should be saturated with refrigerant spray at a distance of 5 mm for 3 s and then placed on the tooth in order to obtain the best results (Jones 1999).

Problem Statement

To date, there have been no studies evaluating the effects of refrigerant spray and crosshead speed on orthodontic composite resin debond strength and ARI score after bond

failure. Based on the premise that composite properties are altered at cold temperatures, mainly due to increased brittleness and microcrack formation, the hypotheses to be tested are as follows:

Hypotheses

1. Shear debond strengths of composite resin bonds between enamel and stainless steel brackets will vary as a result of refrigerant spray use, crosshead speed, or refrigerant spray use and crosshead speed.
2. Debonding location of the orthodontic bracket as measured by the ARI will vary as a function of refrigerant spray use, crosshead speed, or refrigerant spray use and crosshead speed.
3. A correlation between shear debond strength and ARI will vary as a function of refrigerant spray use and crosshead speed.

CHAPTER 2

MATERIALS AND METHODS

Sample Teeth

Third molars are often extracted due to lack of adequate arch space and impaction. Mandibular third molars have less anatomical variation than maxillary third molars and therefore, these teeth are normally used for in vitro testing. All teeth were collected according to UMKC Adult Health Sciences Institutional Review Board exempt protocol collection (Appendix 1). Following extraction, teeth were stored at 4 °C in 0.9% phosphate buffered saline (PBS) solution with 0.002% sodium azide to inhibit microbial growth. There were no personal identifiers linking teeth to specific individuals.

A convenience sample of 40 pairs (right and left) of mandibular third molars was used for this study. Each pair of teeth came from the same individual to help control any confounding variables. Teeth were excluded if any enamel damage was present including enamel craze lines or trauma from extraction forceps. Teeth were inspected for an intact buccal surface with no evidence of carious lesions, demineralization, fluorosis, abfraction lesions, excessively curved buccal surface, restorations or anomalous morphology. If either tooth within the pair met any one of the exclusion criteria for the study, then both teeth were disposed of properly and not used for the study. One tooth from each pair was randomly assigned to either the control group or experimental group.

Specimen Preparation

Mounting of Sample Teeth

The roots of each tooth were secured in self-curing acrylic resin¹ in a mounting ring² with the cemento-enamel junction and anatomical crown exposed. No part of the buccal surface of the tooth crown was contaminated with the acrylic resin during embedding. In order to maintain standard placement of the tooth in the mounting ring, a mounting jig was used to orient the tooth crown with the flattest portion of mesiobuccal enamel perpendicular to the acrylic resin surface (Figure 1). The acrylic resin was allowed to polymerize for one hour prior to removal from the mounting ring.

Bracket Bonding

Brackets were bonded to each tooth following the same protocol. Metal universal twin mandibular second premolar brackets with a slot³ of 0.018 x 0.025-inch cross-sectional dimensions were used in this study. The surface area of the bracket base was 11.61 mm² according to the manufacturer. This was verified by measuring the mesio-distal and occluso-gingival dimensions of the bracket base with a Boley gauge⁴. These brackets have a “Roth” prescription, with built-in angulations defined as 0° “tip” and -22° “torque” to compensate for crown surface anatomy and maximize potential for ideal interdental alignment. These brackets were utilized because in the course of orthodontic treatment, mandibular third molars are not commonly bonded. For this reason, brackets are not manufactured for mandibular third molars. However, the bracket base of the mandibular second premolar usually has the same contours as the mesiobuccal cusp of the mandibular third molar

¹ Biocryl #040-016, Great Lakes, 200 Cooper Ave., Tonawanda, NY 14150

² Item #20-8180, Buehler Ltd., 41 Waukegan Rd., Lake Bluff, IL 60044

³ Victory low profile Roth .018 slot APC brackets, 3M Unitek, 2724 South Peck Rd., Monrovia, CA 91016

⁴ Boley Gauge, Product Code BG, Hu-Friedy, 3232 N. Rockwell St., Chicago, IL 60618

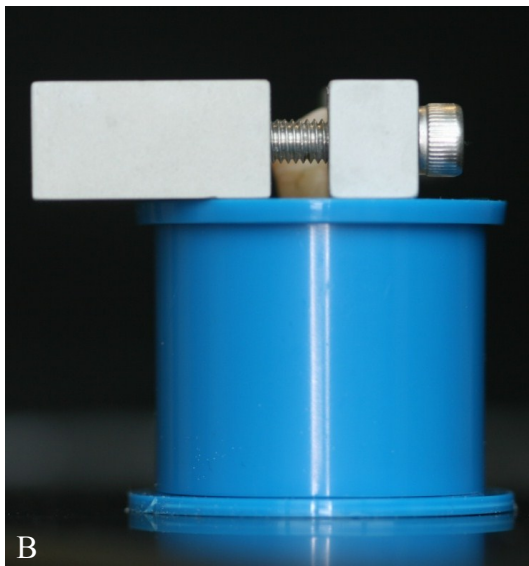
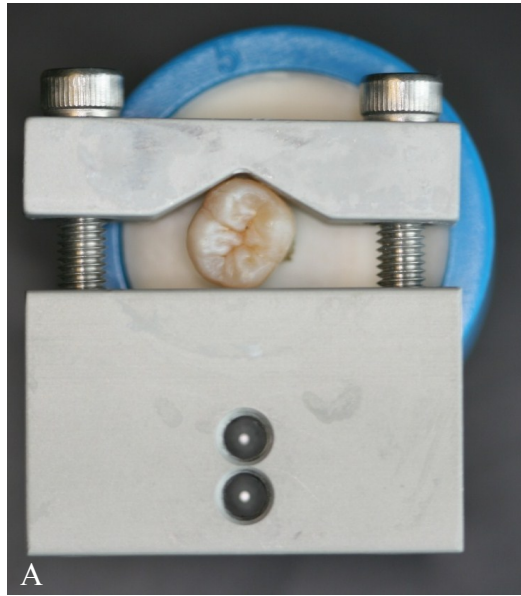


Figure 1. Tooth Mounting Jig and Mounting Ring. Left mandibular third molar secured in mounting jig so the flattest portion of the mesio Buccal enamel surface is perpendicular to the acrylic resin surface. The blue mounting ring was then filled with self-curing acrylic resin to hold the tooth in its proper position. A) Occlusal view, B) Side view

(Ries 2010). Therefore, all mandibular third molars had mandibular second premolar brackets bonded to their mesiobuccal cusp.

Bonding procedures were performed in an environmental chamber at 33 °C (+/-2°) and 75% (+/-3%) humidity to help simulate intraoral temperature and humidity in clinical situations (Plasmans et al. 1994). The mounted tooth was oriented on an external positioning device fabricated from impression putty⁵ so the mesiobuccal cusp surface was parallel to the floor simulating the position of the tooth during intraoral bonding. All procedures were timed with a stopwatch to verify proper timing of all steps. Per manufacturers' instructions, 34% phosphoric acid etch⁶ was applied to the buccal surface for 15 s, rinsed with distilled water for 10 s and air dried for 10 s to ensure the appearance of a frosty enamel surface. A uniform coat of primer⁷ was applied to the etched tooth surface with a disposable brush⁸ followed by a 1 s blast of air to spread the liquid across the tooth surface. After the tooth was etched and primed, a premolar bracket was centered on the flat surface of the mesiobuccal cusp via the pre-coated composite resin adhesive⁹ (70-80% silane treated quartz, 10-20% bisphenol A diglycidyl ether dimethacrylate, 10% bisphenol A bis(2-hydroxyethyl ether) dimethacrylate, <2% silane treated silica, <0.2% diphenyliodonium hexafluorophosphate) on the bracket base (3M 2011). The bracket orientation was adjusted so that the bracket's vertical scribe line was perpendicular to the superior surface of the acrylic resin embedding the tooth. Finger pressure was used to push the bracket against the buccal tooth surface to

⁵ Reprosil Vinyl Polysiloxane Impression Material, 1075 mL tub, Caulk Dentsply Inc., 221 W. Philadelphia Street, P.O. Box 872, York, PA 17405-0872

⁶ Tooth Conditioner Gel 37% Phosphoric Acid, Caulk Dentsply Inc., 221 W. Philadelphia Street, P.O. Box 872, York, PA 17405-0872

⁷ Transbond XT Primer, 3M Unitek, 2724 South Peck Rd., Monrovia, CA 91016

⁸ Microbrush Brand Disposable Micro-Applicator, Microbrush International, 1376 Cheyenne Ave., Grafton, WI 53024

⁹ Transbond XT Light Cure Adhesive, 3M Unitek, 2724 South Peck Rd., Monrovia, CA 91016

create a uniform thickness of composite between the tooth and bracket base. Any excess composite was removed from the periphery of the bracket with a scaler¹⁰. The composite was cured with a light emitting diode¹¹ (LED) according to the manufacturer's recommendations: LED was placed 5 mm from the mesial and distal surfaces of the bracket and cured for 5 s on each side. The LED's power intensity was tested with a radiometer¹² to insure at least 400 mW/cm² output.

Following bracket bonding, the teeth were left undisturbed for 20 mins. A plastic 1.5 cm x 1.5 cm x 1.5 cm grid¹³ was placed in a plastic container with 0.9% PBS solution added to cover the grid. The mounted tooth was inverted and placed on top of the plastic grid so that only the crown of the tooth was submerged in the PBS solution (Figure 2). The container with teeth in PBS solution was covered with a plastic film coating¹⁴ and stored for 24 hrs in an incubator at 37 °C.

Experimental Design

The independent variables of this experimental design were the temperature of the bracket during debonding and the crosshead speed of the universal testing machine. Matched pairs of mandibular third molars were split so that one tooth of each pair was in the experimental group while the other was in the control group. Hence, the control group consisted of 40 teeth that had brackets debonded at room temperature, while the experimental group consisted of 40 teeth that had brackets debonded after exposure to refrigerant spray. The temperature profile of the brackets in the experimental group was established by a pilot

¹⁰ CVHL ½ Hu-Friedy, 3232 N. Rockwell St., Chicago, IL 60618

¹¹ OrthoLux LED, 3M Unitek, 2724 South Peck Rd., Monrovia, CA 91016

¹² OrthoLux LED radiometer, 3M Unitek, 2724 South Peck Rd., Monrovia, CA 91016

¹³ Egg Crate Lighting Panel Model # LP2448EGG-5, The Home Depot, Kansas City, MO 64111

¹⁴ Parafilm M, SPI Supplies/Structure Probe, Inc., West Chester, PA 19380

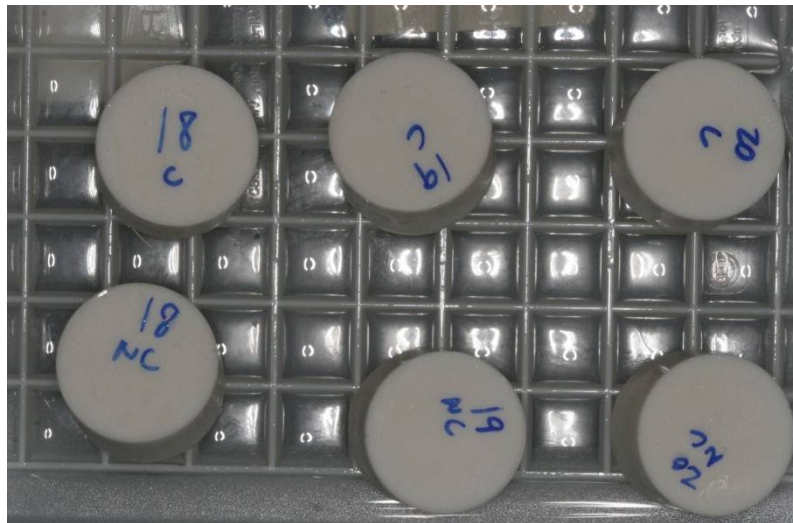


Figure 2. Plastic Container and Grid with Submerged Tooth Crowns. Superior view of plastic container with 0.9% PBS solution, showing labeled resin bases for 6 embedded mandibular third molar teeth. Not visible are the molars with bonded brackets which are supported on the plastic grid and submerged.

test (Appendix 2). The control and experimental groups were divided into two sub-groups according to crosshead speed: the first set of 20 paired teeth had brackets debonded with a crosshead speed of 1 mm/min, while the second set of 20 paired teeth had brackets debonded with a crosshead speed of 10 mm/min. The dependent variables were shear debond strength and location of bond failure based on the ARI. Since one tooth from each pair of teeth was assigned to the control group while the other was assigned to the experimental group, the experiment was a split-mouth group design.

Shear Debond Testing

Control Group

Following 24 hrs of storage in PBS in a 37 °C incubator, brackets were debonded from control specimens using a universal testing machine¹⁵. During testing, the tooth was misted with distilled water from a spray bottle every 30 s to ensure the tooth surface remained moist. The acrylic resin base with tooth embedded was secured on the universal testing machine platform in a mounting device with four locking screws. A knife-edge stainless steel rod attached to the crosshead of the universal testing machine was placed at the occlusal margin of the bracket base and tooth surface (Figure 3). Relative to the tooth's anatomy, the load was applied in a gingival direction and parallel to the buccal enamel surface to remove the bracket using a shear force. To ensure an equivalent starting load for each bracket debond test, a preload of 0.5 N was applied prior to bracket removal at a crosshead speed of either 1 or 10 mm/min. The preload was applied for a total of 25 s before the test was started for all teeth tested. The maximum load (N) was recorded at bond failure

¹⁵ Model 5967, Instron Corporation, 825 University Ave., Norwood, MA 02062-2643

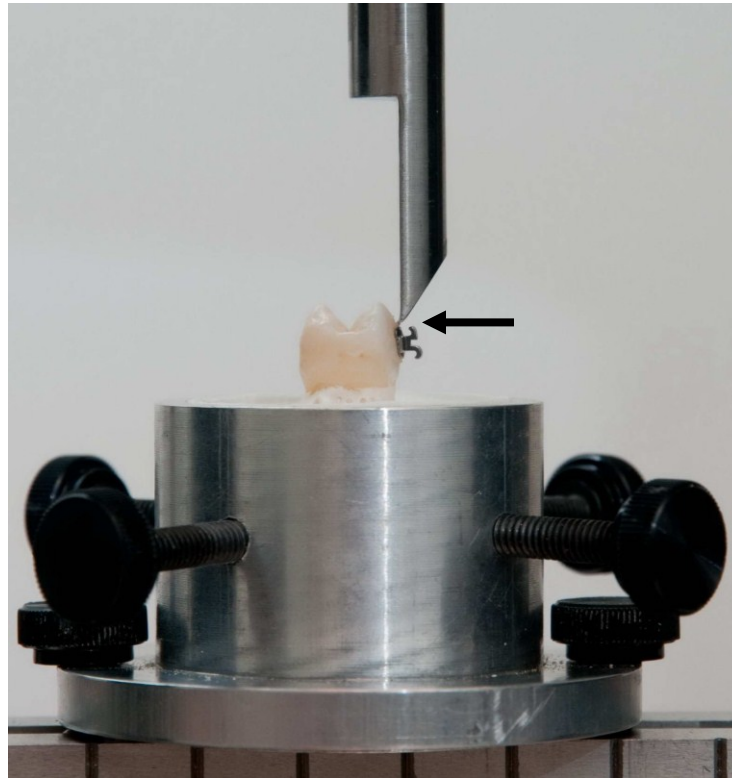


Figure 3. Universal Testing Machine Set-up with Mounted Tooth and Shear Rod. Tooth specimen mounted in acrylic resin base showing base secured to universal testing machine in a mounting device with three visible locking screws. The bracket is positioned with the shearing rod at the occlusal margin of the bracket base (arrow).

by a software program¹⁶.

Experimental Group

For the experimental group, refrigerant spray was applied to the bracket of each specimen prior to debonding. The refrigerant spray aerosol canister was held at a distance of 5.0 mm from a #2 cotton pellet (2 mm in diameter). The cotton pellet was grasped with stainless steel cotton pliers¹⁷ and saturated with the refrigerant spray aerosol for a period of 3 s per manufacturer's recommendations. The refrigerant spray was focused by the aerosol nozzle attached to the aerosol canister. Within 5 s of application of refrigerant spray to the cotton pellet, the cotton pellet was placed against the buccal surface of the bracket for a period of 15 s (determined by pilot tests) without touching the surrounding tooth surface. In order to start the debond test simultaneous with cotton pellet removal, two researchers participated. One held the cotton pellet against the tooth bracket and the other started the test. Then, the same debond protocol as described for the control group was initiated as soon as the cotton pellet with refrigerant spray was removed.

Pilot Testing of Bracket Temperatures

Pilot tests were done to measure the temperature of the bracket over time at baseline (room temperature approximately 23 °C, defined as time -15 s) and following removal of the refrigerant spray-saturated cotton pellet. A K-type thermocouple¹⁸ was secured to the mesio-occlusal tie-wing of the bracket bonded to the mesiobuccal cusp of the embedded mandibular third molar with an adhesive agent¹⁹ (Figure 4). The refrigerant spray-saturated cotton pellet

¹⁶ Bluehill, Instron Corporation, 825 University Ave., Norwood MA 02062-2643

¹⁷ DPU17, Hu-Friedy, 3232 N. Rockwell St., Chicago, IL 60618

¹⁸ K-type thermocouple, OMEGA Engineering, Inc., Stamford, CT 06907

¹⁹ Zapit, Dental Ventures of America, Inc., Corona, CA 92880

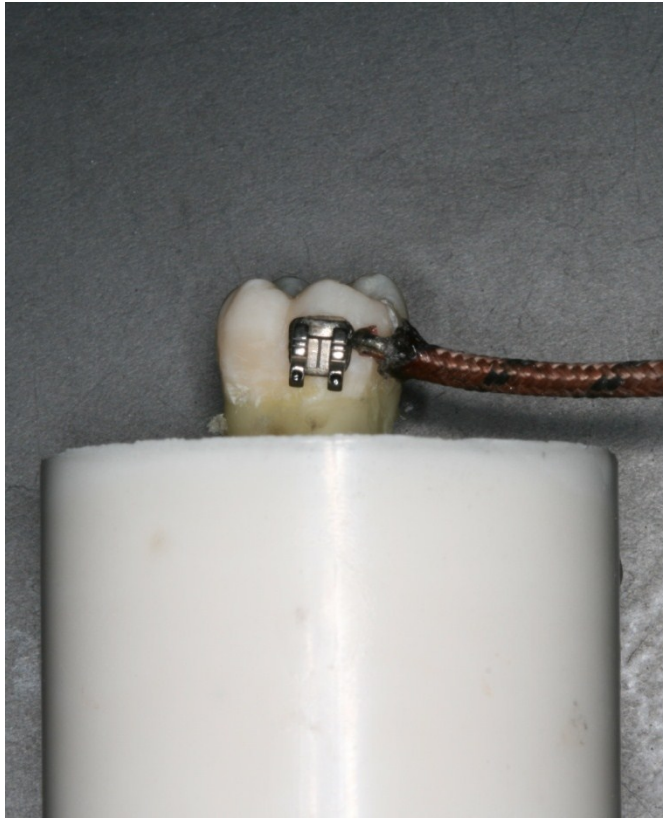


Figure 4. Thermocouple Attached to Bracket for Bracket Temperature Testing. Right mandibular third molar mounted in acrylic resin with bracket bonded to the mesiobuccal cusp. A k-type thermocouple is attached to the mesio-occlusal tie-wing of the bracket in order to record the temperature of the bracket during refrigerant spray application via a cotton pellet.

was placed on the bracket, as described above. Refrigerant spray application times of 10, 15 and 20 s were tested. As soon as the cotton pellet was removed (defined as time 0 s), the temperature of the bracket was recorded and measured every 5 s for 60 s. Once the temperature returned to baseline, the temperature measurements were repeated five times for each bracket for each of the refrigerant spray application times. At 0 s, the mean temperature of the bracket for the 10-s refrigerant spray application group was 11.9 °C with a standard deviation of 1.0 °C. At 0 s, the mean temperature of the bracket for the 15-s refrigerant spray application group was 8.8 °C with a standard deviation of 3.6 °C. At 0 s, the mean temperature of the bracket for the 20-s refrigerant spray application group was 4.1 °C with a standard deviation of 8.5 °C.

Ten tooth specimens were prepared as previously stated and tested in a universal testing machine with a crosshead speed of 1 mm/min at room temperature; the amount of time required to cause bracket debonding was determined (see Appendix 3). From the ten specimens, the maximum compressive load and compressive extension at debonding were recorded. The amount of time required to debond the brackets was calculated based on the compressive extension at debonding and a crosshead speed of 1 mm/min. With these specimens, debond times ranged from 10-27 s. The average test time to debond a bracket was 18.3 s. Using pilot data for the temperature of the bracket, it was determined that for the 10-s refrigerant spray application group, the bracket temperature at 18.3 s would be 14.8 °C. For the 15-s and 20-s refrigerant spray application groups, the bracket temperatures at 18.3 s would be 13.5 °C and 12.6 °C, respectively. It was determined that 15 s of refrigerant spray application would be used for this study for three main reasons. Firstly, 15 s of Endo Ice® application was used previously in vivo without reported adverse effects in research on

pulpal response tests for subjects during active orthodontic treatment and retention (Alomari et al. 2011). If the subject did not report sensitivity after two rounds of 15 s Endo Ice® application, then the tooth was considered to be non-responsive in this previous research. Secondly, the standard deviation for the 15-s refrigerant spray application group in the current study was smaller (Mean 8.8 °C, Standard Deviation (SD) 3.6 °C) than for the 20-s group (Mean 4.1 °C, SD 8.5 °C). Thirdly, the bracket temperature after 15 s of refrigerant spray application (Mean 8.8 °C) was cooler than the bracket temperature after 10 s of refrigerant spray application (Mean 11.9 °C).

Additional pilot tests were performed to determine the temperature of the composite layer after 15 s of refrigerant spray application (See Appendix 4). Two brackets were used for this pilot testing. The brackets were removed from their packaging and the composite cured for 10 s. A thermocouple was secured to the cured composite layer and the bracket was suspended in the air during testing by holding the thermocouple (Figure 5). Refrigerant spray was applied onto a cotton pellet as previously stated and delivered to the buccal surface of the bracket for 15 s. The temperature of the composite layer was recorded prior to refrigerant spray application, immediately after refrigerant spray application and every 5 s for 60 s thereafter. This was repeated five times for each of the two brackets tested. Based on the pilot data, the temperature of the bracket and composite layer were determined if a refrigerant spray-saturated cotton pellet was held against the bracket for 15 s. Prior to the start of testing, the bracket temperature was around 9 °C and the composite layer temperature was around -3 °C. For a crosshead speed of 1 and 10 mm/min, the bracket temperature was around 12 to 15 °C and 9 to 11 °C and the composite layer temperature at debond was



Figure 5. Thermocouple Attached to Cured Composite for Composite Temperature Testing. A bracket with composite cured on the bracket base. A k-type thermocouple is attached to the composite layer in order to record the temperature of the composite layer during a 15 s application time of refrigerant spray delivered to the bracket via a cotton pellet using forceps.

approximately 5 to 14 °C and -3 to -4 °C respectively. This experimental group temperature for both crosshead speeds was lower than the control temperature of approximately 23 °C.

Shear Strength Measurements for Bond Failure

Shear strengths of bond failure for the control and experimental groups were calculated using the following equation: shear strength (MPa) = maximum force to debond (N)/bracket base surface area (mm²).

ARI Measurements

After bracket debonding, the tooth and bracket were recovered and examined under a measuring microscope²⁰ at 1.5-1.8x magnification. Photographs of the tooth and bracket were made with a camera²¹ attached to the measuring microscope and the amount of adhesive remaining on the tooth was classified according to the ARI scoring system developed by Artun and Bergland (1984):

Score 0: no adhesive left on tooth

Score 1: less than half of the adhesive left on the tooth

Score 2: more than half of the adhesive left on the tooth

Score 3: all adhesive left on the tooth, with distinct impression of the bracket mesh

Prior to ARI assessment, the examiner (L.G.) was calibrated. Twenty photos of teeth used for preliminary testing were scored on two different occasions, 48 hrs apart. The photographs were randomly assigned an identifying label which varied from the first to second viewing. ARI scores were determined for each image and intra-rater reliability calculated. There was a 100% agreement between the two scoring sessions.

²⁰ Nikon SMZ800, P-Plan APO 1x WD 70 mm, C-W 10x, Nikon Instrument Inc., 1300 Walt Whitman Road, Melville, NY 11747-3064

²¹ Nikon DXM1200, Nikon Instrument Inc., 1300 Walt Whitman Road, Melville, NY 11747-3064

Statistical Analysis

The shear debond strengths for bracket failures were analyzed using descriptive statistics (means, standard deviations, and ranges) for results of both the control and experimental groups. A 2-factor repeated measures analysis of variance (ANOVA) was used to compare the shear debond strengths between specimen groups subjected to the two temperatures at debond and two crosshead speed variables. More specifically, this test determined if there were statistically significant effects on the shear debond strengths for bracket failure with the use of refrigerant spray and for the different crosshead speeds. ARI measurements were analyzed using the Wilcoxon Matched-Pairs Signed-Rank Test. This test determined if there were statistically significant effects of refrigerant spray application and crosshead speed on the ARI score. A Spearman correlation was done to test any relationship between debond strength and ARI score with the use of refrigerant spray or a change in crosshead speed. Statistical analyses were performed using a statistical analysis software program²². Significance was predetermined at $\alpha = 0.05$.

²² SPSS Inc., 233 South Wacker Drive, Chicago, IL 60606-6307

CHAPTER 3

RESULTS

Shear Debond Strength

The mean (SD) debond strengths for the experimental subgroups with crosshead speeds of 1 and 10 mm/min were 11.09 MPa (4.14 MPa) and 15.43 MPa (4.24 MPa) respectively. The mean (SD) debond strengths for the control subgroups with crosshead speeds of 1 and 10 mm/min were 10.10 MPa (3.53 MPa) and 13.53 MPa (4.18 MPa) respectively. The experimental subgroups had a debond strength range of 3.43-15.13 MPa for the crosshead speed of 1 mm/min and a range of 6.06-24.37 MPa for the crosshead speed of 10 mm/min. The control subgroups had a debond strength range of 1.33-15.54 MPa for the crosshead speed of 1 mm/min and a range of 6.89-20.25 MPa for the crosshead speed of 10 mm/min (Table 1).

The results of the 2-factor repeated measures ANOVA showed no statistically significant difference for shear debond strength as a function of refrigerant spray usage ($p = 0.085$). This did not support part of the first hypothesis. The partial eta squared was 0.148, indicating that only 14.8% of the variation in debond strength can be explained by the use of refrigerant spray. There was also no statistically significant interaction between refrigerant spray usage and crosshead speed on shear debond strength ($p=0.626$). This also did not support part of the first hypothesis. The partial eta squared was 0.013, indicating that only 1.3% of the variation in debond strength can be explained by the use of refrigerant spray and crosshead speed combined. There was however a statistically significant difference for shear debond strength as a function of crosshead speed ($p<0.0001$). As the crosshead speed increased from 1 to 10 mm/min, the debond strength increased. This supported part of the

first hypothesis. The partial eta squared was 0.533, indicating that 53.3% of the variation in debond strength can be explained by the different crosshead speeds.

Debonding Time and Temperature

The mean (SD) bracket debond test times for the experimental subgroups with a crosshead speed of 1 and 10 mm/min were 22.65 s (7.65 s) and 3.65 s (1.50 s) respectively. The mean (SD) bracket debond test time for the control subgroups for a crosshead speed of 1 and 10 mm/min were 22.74 s (9.52 s) and 4.02 s (1.36 s) respectively. For the 1 mm/min crosshead speed, the temperature at the enamel-adhesive interface of the experimental group at the point of debond was between 11 to 13 °C with a temperature differential of 10 to 12 °C between the experimental and control groups when debond occurred. For the 10 mm/min crosshead speed, the temperature at the enamel-adhesive interface of the experimental group at the point of debond was between -3 to -4 °C with a temperature differential of 26 to 27 °C between the experimental and control groups when debond occurred.

Adhesive Residual Index

The adhesive remaining on the tooth surface was evaluated for the experimental and control groups and showed ARI scores of 0, 1, and 3, with an ARI score of 1 most commonly observed (Figure 6, Table 2). For the experimental subgroup with a crosshead speed of 1 mm/min, 3 teeth had an ARI score of 0 and 17 teeth had an ARI score of 1. For the experimental subgroup with a crosshead speed of 10 mm/min, 1 tooth had an ARI score of 0, 18 teeth had an ARI score of 1, and 1 tooth had an ARI score of 3. For the control subgroup with a crosshead speed of 1 mm/min, 6 teeth had an ARI score of 0 and 14 teeth had an ARI score of 1. For the control subgroup with a crosshead speed of 10 mm/min, 1 tooth had an ARI score of 0 and 19 had an ARI score of 1. The Wilcoxon Matched-Pairs Signed-Rank

Test showed no statistically significant difference for ARI score as a function of refrigerant spray usage ($p = 0.166$). This did not support part of the second hypothesis. The Wilcoxon Matched-Pairs Signed-Rank Test was statistically significant for a difference in ARI score as a function of crosshead speed ($p = 0.033$). As the crosshead speed increased from 1 mm/min to 10 mm/min, the amount of residual adhesive remaining on the tooth surface increased. This supported part of the second hypothesis.

Correlation between Debond Strength and ARI Score

A Spearman correlation was performed to test if there was a relationship between the use of refrigerant spray and the crosshead speed with the resulting shear debond strength and ARI score. If refrigerant spray was used prior to debonding, regardless of crosshead speed, there was no statistically significant correlation between debond strength and ARI score ($p=0.128$ for 1 mm/min, $p=0.914$ for 10 mm/min). If no refrigerant spray was used and the crosshead speed was 1 mm/min, there was no statistically significant correlation between debond strength and ARI score ($p=0.225$). However, if there was no refrigerant spray used and the crosshead speed was increased to 10 mm/min, there was a moderate correlation between debond strength and ARI score ($p=0.040$).

TABLE 1

DESCRIPTIVE STATISTICS OF THE BRACKET DEBOND STRENGTHS FOR THE EXPERIMENTAL AND CONTROL GROUPS AS A FUNCTION OF CROSSHEAD SPEED

Refrigerant Spray Use*	Experimental Groups		Control Groups	
Crosshead Speed (mm/min) ⁺	1	10	1	10
Sample Size	20	20	20	20
Mean Debond Strength (MPa)	11.09	15.43	10.10	13.53
Standard Deviation	4.14	4.24	3.53	4.18
Range (MPa)	3.43-15.13	6.06-24.37	1.33-15.54	6.89-20.25

* No statistically significant difference in shear debond strength as a function of refrigerant spray use ($p = 0.085$)

⁺ Statistically significant difference in shear debond strength as a function of crosshead speed ($p < 0.0001$)

TABLE 2

FREQUENCY DISTRIBUTION OF THE ARI SCORES OF THE EXPERIMENTAL AND CONTROL GROUPS

Refrigerant Spray Use*		Experimental Groups		Control Groups	
Crosshead Speed (mm/min) ⁺		1	10	1	10
Sample Size		20	20	20	20
ARI Score	0	3	1	6	1
	1	17	18	14	19
	2	0	0	0	0
	3	0	1	0	0

* No statistically significant difference in ARI scores as a function of refrigerant spray use (p = 0.166)

⁺ Statistically significant difference in ARI scores as a function of crosshead speed (p = 0.033)

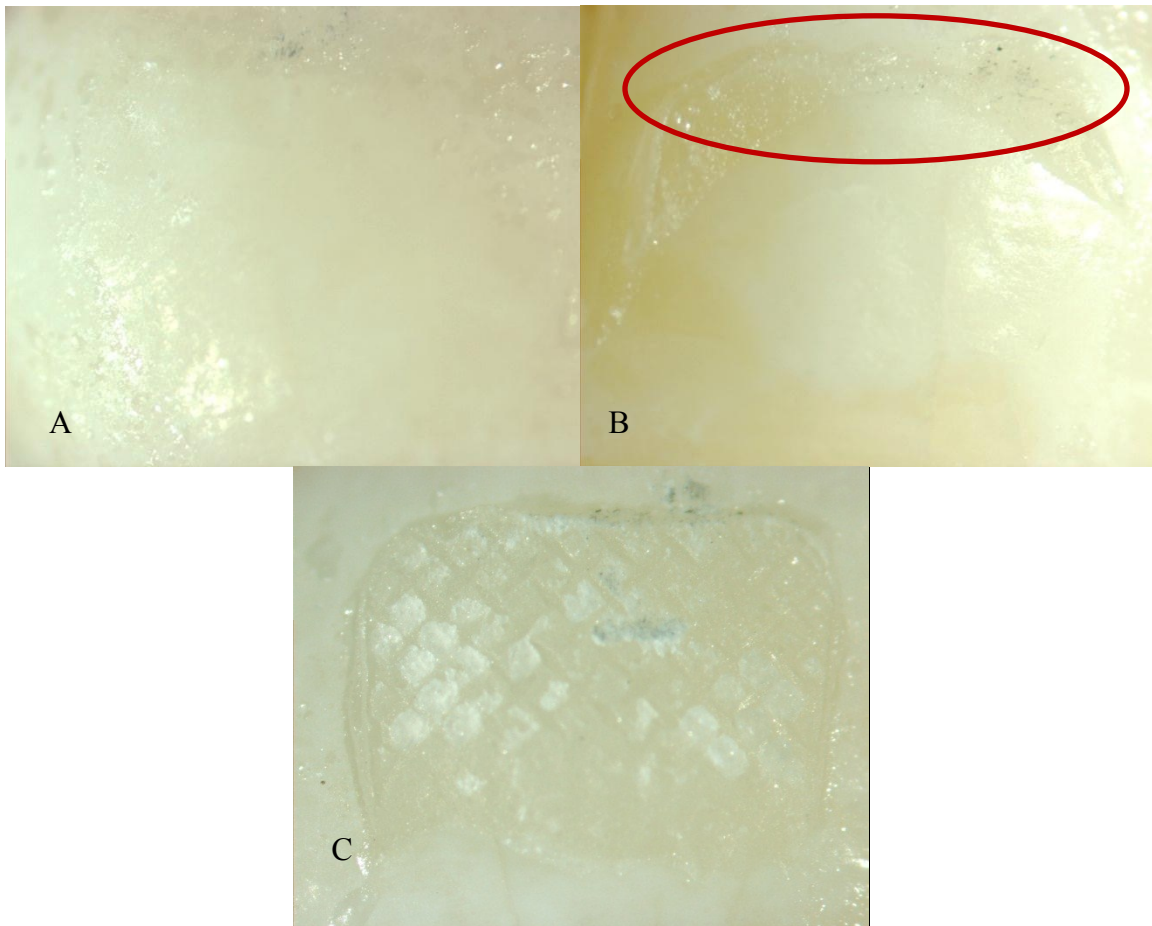


Figure 6. ARI Score Examples. All of the teeth tested had an ARI score of 0, 1, or 3. A) Example of ARI score 0. B) Example of ARI score 1 with residual adhesive circled. C) Example of ARI score 3.

CHAPTER 4

DISCUSSION

In this study, the effects of refrigerant spray and crosshead speed on shear debond strength and ARI score were assessed. Although there have been other studies that have evaluated the effect of crosshead speed on shear debond strength and ARI score, no other known study has tested the effect of refrigerant spray or the combined effects of refrigerant spray and crosshead speed on these variables (Lindemuth and Hagge 2000; Eliades et al. 2004; Bishara et al. 2005; Klocke and Kahl-Nieke 2005a). The current study found statistically significant differences for both shear debond strength and ARI score as a function of crosshead speed, but not as a function of refrigerant spray use.

The results showed that the use of refrigerant spray prior to debonding does not significantly affect the debond strength or the ARI score. Previous research has been performed on composites used as structural reinforcement in bridges and columns in cold weather environments. These studies found that when composites were exposed to extremely cold temperatures for a prolonged period of time (-35 °C) they became increasingly brittle and rigid (Karbhari and Eckel II 1994; Nordin et al. 2010). It is difficult to compare these industrial composites to dental composites due to the different physical, structural, and chemical composition. However, there have been no studies performed, to the researchers' knowledge, that test the physical properties of dental composites at extremely cold temperatures, and more specifically orthodontic bonding composites at extremely cold temperatures. The failure of cold application to affect bracket debond strength and ARI score is most likely related to the difference in composite composition and the lack of sustained cold temperature prior to debonding. For the 1 and 10 mm/min test groups, the

highest temperature differentials of the composite layer between the control and experimental groups were approximately 18 °C and 26 °C, respectively. Possibly a more prolonged exposure to the cold temperature would have increased the temperature differential between the experimental and control groups which might have decreased the debond strength and increased the ARI score. However, an increase in exposure to the refrigerant spray would have caused increased tooth sensitivity and possible pulpal damage (Jones et al. 2002). The use of 15 s of refrigerant spray application was based on a previous study which reported no adverse effects in subjects with an application time of 15 s (Alomari et al. 2011). Also the composite layer at debond reached a low temperature of -4 °C, whereas normal intraoral temperatures range between 0-67 °C based upon the temperature of liquids and solids consumed (Palmer et al. 1992; Linsuwanont et al. 2008). The composite temperature was only 4 °C less than the normal intraoral temperature range, and this lack of temperature extreme could have contributed to the results. If the mean debond strengths between the control and experimental groups are compared for each crosshead speed, the means for the experimental group were higher than those of the control group. This may indicate that using refrigerant spray prior to debonding might actually increase the debond strength. The low temperature could momentarily increase the strength of the composite molecular structure before a brittle fracture occurs. However, additional studies are required to test the effects of cold temperatures on the physical and structural properties of orthodontic composites.

The debond strength results ranged from 1.33-24.37 MPa, with 49 of the 80 samples ranging from 8.0-16.0 MPa. These values are greater than the range of clinically acceptable bond strengths stated by Reynolds (Reynolds 1975). He recommended bond strengths should be between 6-8 MPa. However, this range of values is purely a recommendation

based on an article he wrote from 1975 that reviewed materials and procedures used for direct bracket bonding. According to Scopus, this article has been cited 555 times as of June 2012, but the citation is inappropriate because these values have not been validated. That is, these values have never been tested and therefore, comparison of bond strengths to this range of suggested clinically acceptable values should be avoided.

Research has shown that in vitro debond strengths are greater than in vivo debond strengths. In a study performed by Pickett et al. (Pickett et al. 2001) a comparison between in vitro and in vivo debonding forces using a universal testing machine and intraoral debonding plier were assessed. Debonding forces in vitro were 11.02 MPa whereas those in vivo were 5.47 MPa. In vivo debond strengths were 49.6% lower than in vitro debond strengths. Therefore, if the average debond strength of 12.5 MPa from the current study was used and the same differential applied, the estimated in vivo debond strength would be 6.20 MPa. Although this value is slightly higher than the value seen in the Pickett et al. study, it is still considered a clinically acceptable value (Lopez 1980; Pickett et al. 2001). It can be concluded that the debond strengths reported in this study are comparable to other studies and can be considered clinically acceptable.

It was reported by Bishara and co-authors (Bishara et al. 1995) that excessive debonding strengths of greater than 11.1 MPa were more likely to cause enamel damage, but that at debonding strengths lower than 7.1 MPa, enamel damage was less probable. All of the teeth tested in our study were examined following testing and only 4 of the 80 tested teeth had enamel fractures. Out of the 34 test teeth that had debond strengths of less than 11.1 MPa, only 1 of those teeth had enamel damage. Out of the remaining 46 teeth that had debond strengths greater than 11.1 MPa, 3 of those teeth had enamel damage. All 4 teeth

with enamel fractures were tested with a crosshead speed of 10 mm/min, and 3 of the 4 teeth had refrigerant spray applied to the bracket prior to debonding. The debond strengths of these 4 teeth ranged from 10.35-16.15 MPa. Although 11.1 MPa may not be a threshold value for enamel damage, it can be concluded that it is a reasonable value to use as a marker for potential enamel damage, as only 1 tooth with a debond strength of less than 11.1 MPa had enamel fracture and its debond strength was greater than 7.1 MPa. Therefore, the results are comparable to Bishara and co-authors.

The results of the current study suggest that the use of refrigerant spray prior to bracket debonding might actually increase the risk of enamel damage. This suggestion is based on the finding that 3 of the 4 tested teeth with enamel damage had refrigerant spray used prior to debonding. The current results also suggest that the use of a slower debond speed may decrease potential enamel damage, because all of the teeth with enamel damage were tested with a faster crosshead speed.

In regards to the test results for ARI scores, 85% of teeth tested had ARI scores of 1, correlating to less than 50% of adhesive remaining on the tooth after debond. The hopes were to find a new debond method utilizing refrigerant spray to remove brackets that would allow for less adhesive clean-up and minimal enamel damage. However, the results indicate that regardless of refrigerant spray usage, there was no difference in ARI scores. What was found was that as the crosshead speed increased, the ARI scores also increased. Therefore if greater speed is used when debonding brackets clinically, more residual adhesive may remain on the tooth surface. A common method to debond stainless steel orthodontic brackets in vivo uses an orthodontic debonding plier. This method involves a controlled squeezing motion applied to the handles of the plier. The plier blades are placed at either the bracket

enamel interface or between the bracket tie-wings. Via this method, a bracket is normally debonded within about 1-2 seconds. Therefore, this controlled motion most likely mimics the faster crosshead speed of 10 mm/min. The average time required to debond a bracket with a crosshead speed of 10 mm/min was 3.84 s, whereas it was 22.7 s with a crosshead speed of 1 mm/min. It appears that although the 1 mm/min crosshead speed has been a standard testing parameter for debond strengths, a 10 mm/min crosshead speed might be more clinically relevant due to the time required to debond a bracket.

The results of this study indicate that as the crosshead speed increased from 1 to 10 mm/min, the debond strengths also increased. Based on a systematic review by Finnema et al. (Finnema et al. 2010), as the crosshead speed increased by 1 mm/min, the debond strength was predicted to increase by 1.3 MPa. If a comparison is done between the 1 and 10 mm/min crosshead speed data collected in the current study, an increase in crosshead speed of 1 mm/min only increased the debond strength by 0.43 MPa on average, not the 1.3 MPa Finnema et al. reported. Although the increase in debond strength with an increase in crosshead speed was less than that seen in the review by Finnema and colleagues, it still had a similar pattern. The lower value might be due to the differences in crosshead speeds used in the comparison. The crosshead speeds that were compared in the systematic review ranged from 0.1 to 5.0 mm/min, whereas only two crosshead speeds of 1 and 10 mm/min were tested in this study. Since only two crosshead speeds were tested in our study, at best only a linear relationship could be assumed. Lindemuth and Hagge (Lindemuth and Hagge 2000) theorized that there is a transition from a viscoelastic to a brittle material behavior for composites as the crosshead speed increases. However, in order to prove this theory, a wider range of data points is needed, especially at crosshead speeds faster than 10 mm/min. Thus,

additional studies need to be performed to better understand the relationship between crosshead speed and debond strength.

Limitations

A major limitation of this study, in addition to testing only 2 cross-head speeds as previously discussed, was that testing was performed in vitro. Any in vitro study has its limitations when trying to apply the results in vivo. Although all efforts were made to obtain environmental conditions that mimic clinical conditions, the efficacy of refrigerant spray use on debond strength and ARI score can only truly be evaluated in the environment in which brackets are normally debonded, the oral cavity.

Third molar teeth were used in this study which also was a limitation. Although a previous study found the mesiobuccal cusp of mandibular third molars to mimic the contours of the buccal surface of a mandibular second premolar, the bracket that was used was not manufactured for third molar teeth (Ries 2010). This could have affected the results due to lack of proper adaptation of the bracket base to the tooth surface. The mandibular third molar teeth that were used in this study were either completely bony impacted, and therefore never erupted into the oral cavity, or were partially bony impacted, in which a portion of the crown of the tooth was erupted into the oral cavity. These teeth therefore were not subjected to the different oral conditions that would be present if the teeth were fully erupted. Therefore, it is difficult to conclude that our results can be generalized to fully erupted teeth that are normally bonded with brackets for orthodontic treatment.

Another limitation is that the actual temperature of the bracket and composite layer during debond was not directly measured for each specimen. An average temperature was calculated from pilot data to determine the temperature differential between the experimental

and control groups. In order to have a better understanding of the difference in temperature between the experimental and control groups, an actual measurement of the temperature of the bracket and composite layer at debond would have been beneficial.

The typical treatment time for orthodontic patients is around two years. During this time, the brackets are exposed to different environmental conditions including variations in temperature, pH, bacteria, fluoride concentrations, water absorption, and other disturbances. None of these environmental conditions were taken into account with the current study. All teeth were tested 24 hours after bracket bonding. This short time period between bracket bonding and debonding is not typical and may not fully account for the changes and aging effects that can be seen over time with orthodontic materials.

When measuring debond strengths, the normal units of measurement are megapascals. However, a more appropriate measure to use might be the amount of energy absorbed by the material in order to debond a bracket. When results are calculated using the maximum force required to debond a bracket, only a singular point in time is represented. Whereas if results were presented based upon the amount of energy absorbed prior to debond, it might better capture the effects on material properties over time, rather than at one singular time-point. For future studies, it might be advantageous to report findings both as the amount of energy absorbed and the maximum force required to debond so the full effect on a material can be understood.

Clinical Implications

The results from this study indicate that the use of refrigerant spray prior to debonding an orthodontic bracket had no significant effect on the shear debond strength or ARI score. Overall, the debond strengths and ARI scores of the experimental group were

higher than the control group. This suggests that the use of refrigerant spray prior to debonding, not only requires increased force, but it might actually increase the risk of enamel damage. The amount of adhesive remaining on the tooth structure was also higher, so refrigerant spray use produced a bond failure that would require more clean-up time. Therefore, it is not suggested to use refrigerant spray prior to debonding.

Increases in shear debond strength and ARI score were seen with an increase in crosshead speed. This suggests that if a quick, swift motion is used when debonding, it could increase the risk of enamel damage, and has the potential of leaving more adhesive on the tooth. Therefore, it is suggested to use a controlled, slower speed when debonding orthodontic brackets.

Future Studies

Future studies could focus on identifying the effects of cold temperatures on the physical and structural properties of orthodontic composite resins. Composite resins used for orthodontic purposes are different from composite resins used for dental restorations, and therefore the properties of these materials need to be researched. With orthodontic composite resins, a thin layer of material is used to bond a bracket to a tooth, whereas with composite resins used for dental restorations, a thicker layer is used. This difference in layer thickness might have an effect on the material's properties.

For future studies that utilize paired teeth and a split mouth study design, it may be helpful to report the percent difference between the paired sample teeth. This percent difference calculation would help normalize for the sort of high inter-specimen variability that was apparent in the current study.

Additional studies need to be performed on bracket debonding techniques and procedure standardization. This study identifies a need to determine a crosshead speed which is clinically relevant. A crosshead speed of 0.1-0.5 mm/min had been previously suggested as a crosshead speed to use for standardization of testing protocol (Eliades et al. 1991; Fox et al. 1994; Kao et al. 1995). However, the lack of clinical relevance of this range of speeds has been proposed by Eliades and Brantley who state that “in vivo debonding incidents are expected to occur at much higher impact velocity, where viscoelastic behaviour of the adhesive, which may be important at low cross-head speeds, is largely absent” (Eliades and Brantley 2000). It is inferred from this study that a model needs to be developed that can be used in vitro to simulate in vivo debond strengths. Possibly the use of a crosshead speed of 10 mm/min might be more representative of what is observed in vivo. It can be concluded that additional research needs to be performed to determine a more clinically relevant crosshead speed, whether that is 10 mm/min or faster.

CHAPTER 5

CONCLUSIONS

The following conclusions can be made from this in vitro study:

1. Bracket shear debond strength and location of debond were not significantly altered as a result of refrigerant spray use prior to debonding.
2. Bracket shear debond strength and location of debond were significantly altered as a result of crosshead speed. As crosshead speed increased from 1 mm/min to 10 mm/min, bracket shear debond strength increased and more residual adhesive remained on the tooth surface.
3. Based on these results and within the limitations of this study, it does not appear to be beneficial to apply refrigerant spray prior to bracket debonding.

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APPENDIX 1
IRB APPROVAL

Research Protocol

Anderman, Sheila H.

Sent: Monday, January 31, 2011 3:42 PM

To: Gossett, Lauren A. (UMKC-Student); Iwasaki, Laura R.

Cc: Purk, John

Dear Investigators:

Thank you for notifying the IRB of your intent to do research. It is the policy of the University to determine whether your study involves human subjects and/or if it is exempt from IRB review. This email is to inform you that the UMKC Adult Health Sciences Institutional Review Board completed a review of your protocol entitled, "Effect of refrigerant spray on Orthodontic composite resin bond strength and adhesive remnant index" and has determined that this project does not involve human subjects research since you will be using teeth that have already been extracted and in your possession (with no identifiers).

For this reason, we have determined that the UMKC Adult Health Sciences Institutional Review Board is not required to review your research project. Should you have any questions regarding this correspondence, please don't hesitate to contact me.

Please contact Dr. Purk for any Privacy concerns.

Good luck with your research!

Sheila H. Anderman, CIP, CIM
Research Protections Program Manager
Office of Research Services
University of Missouri-Kansas City
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APPENDIX 2
BRACKET TEMPERATURE PILOT DATA

TABLE 3

TEMPERATURE OF BRACKET AT BASELINE (-10 s) AND AFTER EXPOSURE TO A REFRIGERANT SPRAY-SATURATED COTTON PELLET FOR 10 s THEN REMOVAL OF PELLET (0 s)

Time (s)	Temperature (°C)					Mean (Standard Deviation)
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	
-10	18.8	17.6	18.8	19.0	18.7	18.6 (0.6)
0	10.8	11.4	12.2	13.5	11.5	11.9 (1.0)
5	12.0	12.8	12.8	13.8	12.7	12.8 (0.6)
10	13.1	13.6	13.7	14.4	13.8	13.7 (0.5)
15	14.0	14.3	14.3	15.2	14.2	14.4 (0.5)
20	14.7	14.8	14.9	15.8	14.8	15.0 (0.5)
25	15.3	15.1	15.3	16.2	15.5	15.5 (0.4)
30	15.7	15.4	15.7	16.5	15.7	15.8 (0.4)
35	16.0	15.7	16.0	16.8	16.2	16.1 (0.4)
40	16.3	16.0	16.3	17.0	16.5	16.4 (0.4)
45	16.5	16.2	16.6	17.2	16.8	16.7 (0.4)
50	16.7	16.3	16.8	17.4	17.0	16.8 (0.4)
55	17.0	16.5	16.9	17.5	17.2	17.0 (0.4)
60	17.2	16.6	17.1	17.7	17.4	17.2 (0.4)

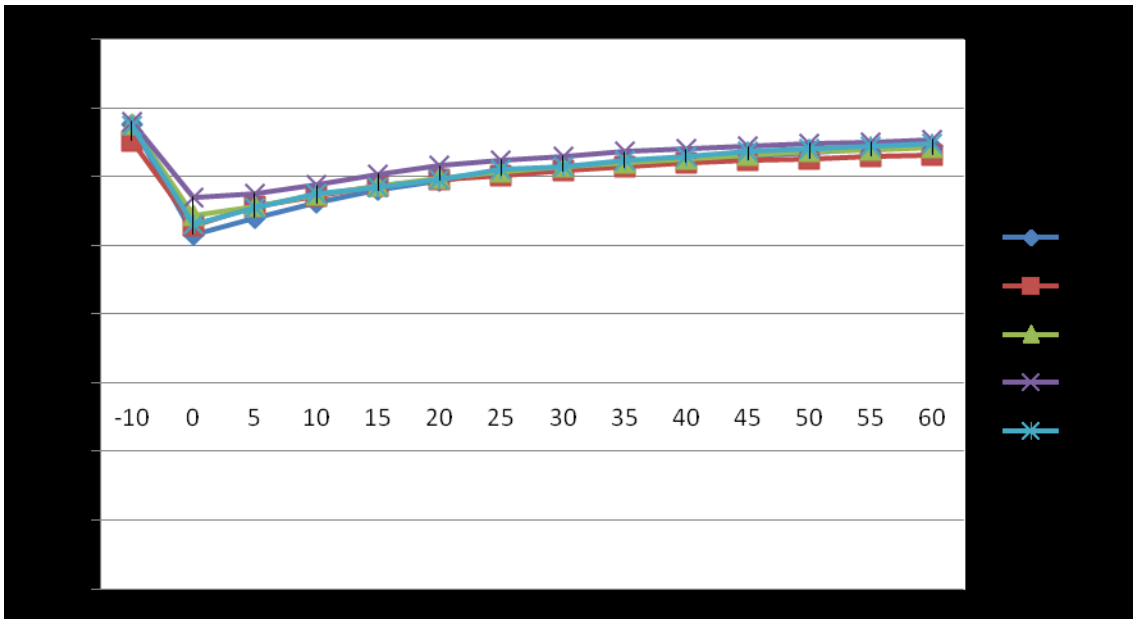


Figure 7. Graph of Temperature versus Time for an Orthodontic Bracket for 10 seconds of Refrigerant Spray Application Time. Temperature (°C) of the bracket versus time (s) where temperature at -10 s represents the baseline temperature right before refrigerant spray application with a saturated cotton pellet. 0 s represents when the refrigerant spray saturated cotton pellet was removed from the bracket. The temperature was recorded every 5 s thereafter for 60 s. The test with refrigerant spray was repeated 5 times and the temperature recorded (series 1-5).

TABLE 4

TEMPERATURE OF BRACKET AT BASELINE (-15 s) AND AFTER EXPOSURE TO A REFRIGERANT SPRAY-SATURATED COTTON PELLET FOR 15 s THEN REMOVAL OF PELLET (0 s)

Time (s)	Temperature (°C)					Mean (Standard Deviation)
	Trial 1	Trial 2	Trial 3	Trail 4	Trail 5	
-15	18.8	17.8	19.1	19.0	19.0	18.7 (0.5)
0	6.4	9.5	12.2	4.0	12.1	8.8 (3.6)
5	8.4	11.1	13.0	7.4	12.7	10.5 (2.5)
10	10.2	12.7	13.6	10.0	13.4	12.0 (1.7)
15	11.1	13.7	14.3	11.4	14.0	12.9 (1.5)
20	12.1	14.5	15.1	12.8	14.7	13.8 (1.3)
25	12.9	14.9	15.6	13.7	15.2	14.5 (1.1)
30	13.5	15.4	16.0	14.2	15.6	14.9 (1.0)
35	14.0	15.8	16.2	14.8	16.0	15.4 (0.9)
40	14.5	16.0	16.5	15.3	16.4	15.7 (0.8)
45	14.8	16.2	16.7	15.7	16.6	16.0 (0.8)
50	15.2	16.4	16.9	16.0	16.7	16.2 (0.7)
55	15.5	16.6	17.1	16.2	16.9	16.5 (0.6)
60	15.8	16.8	17.3	16.4	17.1	16.7 (0.6)

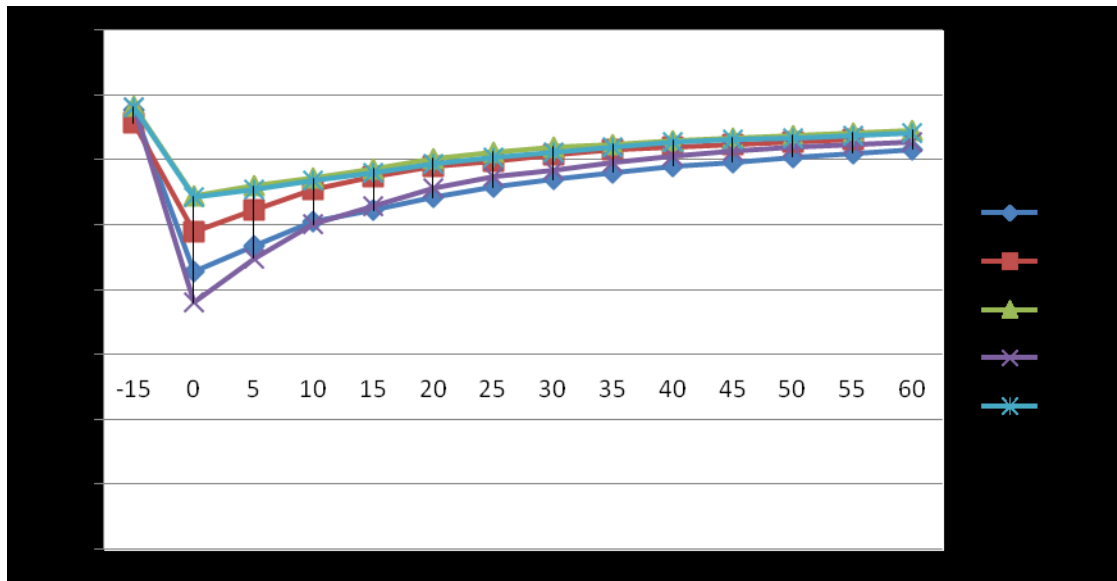


Figure 8. Graph of Temperature versus Time for an Orthodontic Bracket for 15 seconds of Refrigerant Spray Application Time. Temperature ($^{\circ}\text{C}$) of the bracket versus time (s) where temperature at -15 s represents the baseline temperature right before refrigerant spray application with a saturated cotton pellet. 0 s represents when the refrigerant spray saturated cotton pellet was removed from the bracket. The temperature was recorded every 5 s thereafter for 60 s. The test with refrigerant spray was repeated 5 times and the temperature recorded (series 1-5).

TABLE 5

TEMPERATURE OF BRACKET AT BASELINE (-20 s) AND AFTER EXPOSURE TO A REFRIGERANT SPRAY-SATURATED COTTON PELLETT FOR 20 s THEN REMOVAL OF PELLETT (0 s)

Time (s)	Temperature (°C)					Mean (Standard Deviation)
	Trial 1	Trial 2	Trial 3	Trail 4	Trail 5	
-20	18.8	18.5	19.0	19.0	19.0	18.9 (0.2)
0	-10.8	8.6	4.5	9.2	8.8	4.1 (8.5)
5	-3.0	9.3	7.4	10.7	10.2	6.9 (5.7)
10	1.2	10.8	9.6	11.7	11.5	9.0 (4.4)
15	4.1	11.7	11.0	12.8	12.4	10.4 (3.6)
20	6.9	12.9	12.3	13.7	13.2	11.8 (2.8)
25	9.0	13.6	13.0	14.3	13.9	12.8 (2.2)
30	10.0	14.2	13.7	14.8	14.4	13.4 (2.0)
35	11.3	14.7	14.3	15.2	14.8	14.1 (1.6)
40	12.1	15.2	14.9	15.6	15.3	14.6 (1.4)
45	13.0	15.6	15.4	16.0	15.6	15.1 (1.2)
50	13.8	15.9	15.7	16.3	15.9	15.5 (1.0)
55	14.4	16.2	16.1	16.5	16.1	15.9 (0.8)
60	14.8	16.4	16.4	16.7	16.4	16.1 (0.8)

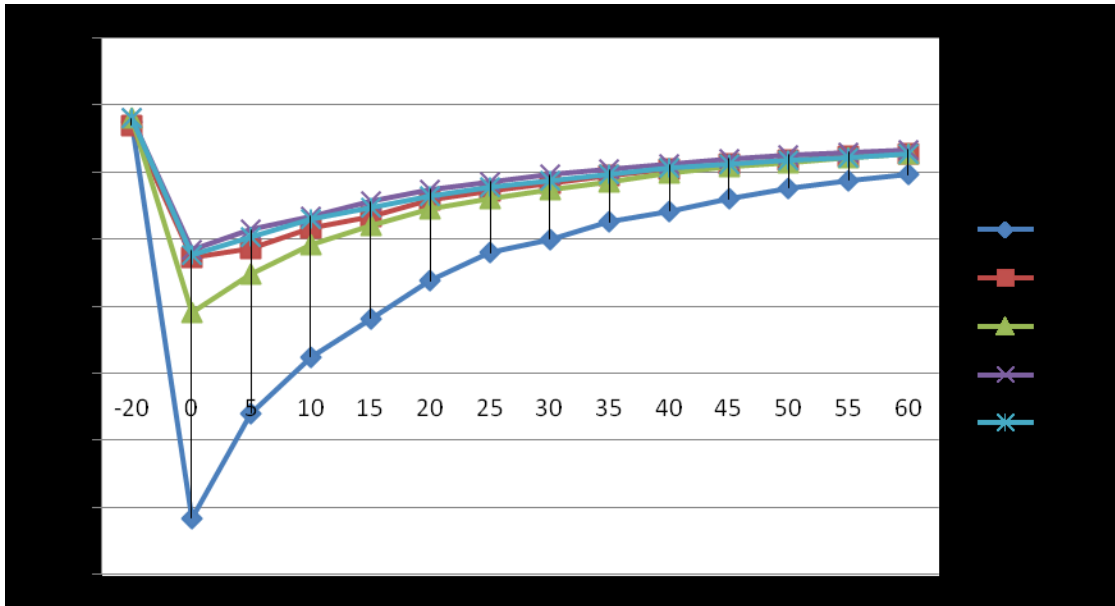


Figure 9: Graph of Temperature versus Time for an Orthodontic Bracket for 20 seconds of Refrigerant Spray Application Time. Temperature ($^{\circ}\text{C}$) of the bracket versus time (s) where temperature at -20 s represents the baseline temperature right before refrigerant spray application with a saturated cotton pellet. 0 s represents when the refrigerant spray saturated cotton pellet was removed from the bracket. The temperature was recorded every 5 s thereafter for 60 s. The test with refrigerant spray was repeated 5 times and the temperature recorded (series 1-5).

APPENDIX 3

BRACKET DEBOND TIME PILOT DATA

TABLE 6

TEST DURATION AND SUBSEQUENT MAXIMUM COMPRESSIVE LOAD AND COMPRESSIVE EXTENTION AT BRACKET DEBOND

Tooth Number	Cusp	Maximum Compressive Load (N)	Compressive Extension at Maximum Compressive Load (mm)	Test Time (s)
1	MB	99.52	0.16	9.6
1	DL	115.46	0.18	10.8
2	MB	158.65	0.43	25.8
2	DL	159.14	0.38	22.8
3	MB	193.60	0.45	27.0
3	DL	108.55	0.28	16.8
4	MB	143.39	0.23	13.8
4	DL	206.24	0.28	16.8
5	MB	119.70	0.41	24.6
5	DL	231.37	0.35	21.0

Table 6: Ten brackets were bonded to either the mesiobuccal (MB) or distolingual (DL) cusp of a mandibular third molar. The brackets were tested in a universal testing machine at room temperature. The maximum compressive load (N) and compressive extension (mm) at debonding were recorded. The amount of time (s) required to debond the brackets was calculated based on the compressive extension at debonding and a crosshead speed of 1 mm/min.

APPENDIX 4

BRACKET COMPOSITE LAYER TEMPERATURE PILOT DATA

TABLE 7

BRACKET NUMBER ONE: TEMPERATURE OF COMPOSITE LAYER AT BASELINE (-15 s) AND AFTER EXPOSURE TO A REFRIGERANT SPRAY-SATURATED COTTON PELLETT FOR 15 s THEN REMOVAL OF PELLETT (0 s)

Time (s)	Temperature (°C)					Mean (Standard Deviation)
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	
-15	22.2	22.4	22.4	22.4	22.2	22.3 (0.1)
0	2.1	0.0	-1.2	-5.0	-3.0	-1.4 (2.7)
5	6.5	2.4	1.8	0.7	0.9	2.5 (2.4)
10	10.8	6.0	6.2	6.0	6.1	7.0 (2.1)
15	12.8	9.0	10.0	9.6	10.2	10.3 (1.5)
20	14.4	12.0	11.9	12.3	12.1	12.5 (1.1)
25	15.4	13.5	13.8	13.6	13.7	14.0 (0.8)
30	16.4	14.9	15.0	14.7	15.0	15.2 (0.7)
35	17.1	15.8	15.9	15.7	15.9	16.1 (0.6)
40	17.7	16.5	16.6	16.3	16.7	16.8 (0.5)
45	18.2	17.2	17.2	17.0	17.2	17.4 (0.5)
50	18.5	17.9	17.8	17.4	17.7	17.9 (0.4)
55	18.8	18.3	18.2	17.9	18.2	18.3 (0.3)
60	19.0	18.6	18.5	18.3	18.5	18.6 (0.3)

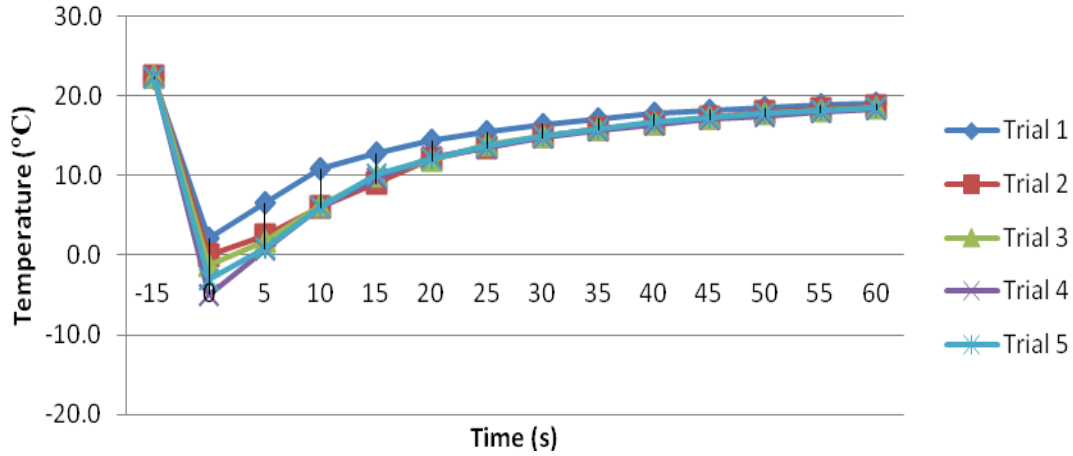


Figure 10: Bracket Number One: Graph of Temperature versus Time for the Composite Layer for 15 seconds of Refrigerant Spray Application Time. Temperature ($^{\circ}\text{C}$) of the composite layer versus time (s) where temperature at -15 s represents the baseline temperature right before refrigerant spray application with a saturated cotton pellet. 0 s represents when the refrigerant spray saturated cotton pellet was removed from the bracket. The temperature was recorded every 5 s thereafter for 60 s. The test with refrigerant spray was repeated 5 times and the temperature recorded (Trial 1-5).

TABLE 8

BRACKET NUMBER TWO: TEMPERATURE OF COMPOSITE LAYER AT BASELINE (-15 s) AND AFTER EXPOSURE TO A REFRIGERANT SPRAY-SATURATED COTTON PELLETT FOR 15 s THEN REMOVAL OF PELLETT (0 s)

Time (s)	Temperature (°C)					Mean (Standard Deviation)
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	
-15	22.8	22.0	22.8	22.7	23.0	22.7 (0.4)
0	-15.0	-12.5	-6.2	0.7	-2.5	-7.1 (6.6)
5	-9.2	-6.9	-4.6	4.3	1.1	-3.1 (5.6)
10	-1.7	-0.7	2.1	7.8	5.1	2.5 (4.0)
15	3.2	3.7	6.1	10.8	8.7	6.5 (3.2)
20	7.7	7.6	9.2	13.3	11.7	9.9 (2.5)
25	10.1	10.8	12.2	14.6	14.0	12.3 (2.0)
30	12.4	12.5	13.8	15.8	15.2	13.9 (1.5)
35	13.8	14.0	15.1	16.7	16.0	15.1 (1.3)
40	15.0	15.1	16.1	17.4	16.8	16.1 (1.0)
45	15.7	16.0	16.8	18.1	17.4	16.8 (1.0)
50	16.3	16.6	17.3	18.6	17.9	17.3 (0.9)
55	16.8	17.2	17.8	18.9	18.3	17.8 (0.8)
60	17.3	17.7	18.2	19.3	18.8	18.3 (0.8)

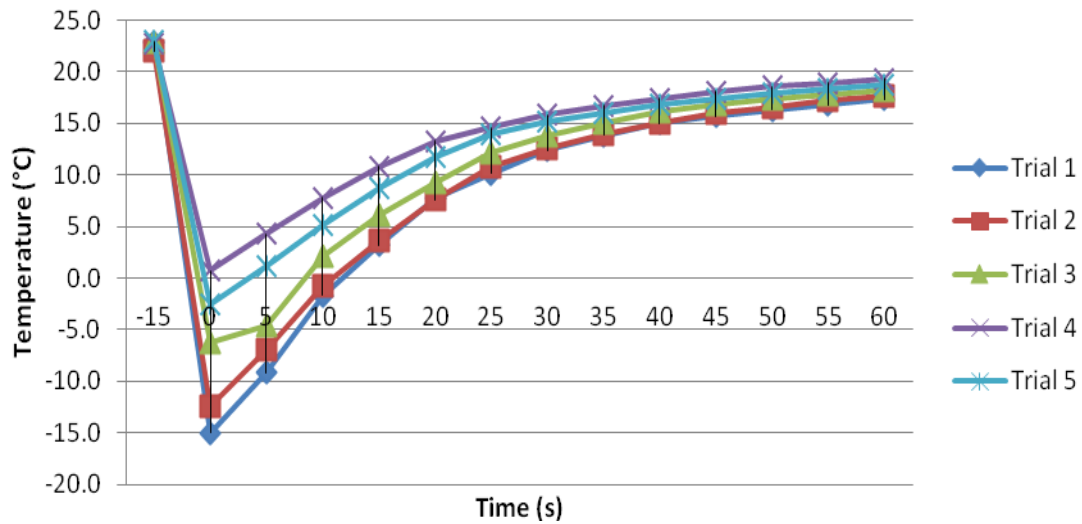


Figure 11: Bracket Number Two: Graph of Temperature versus Time for the Composite Layer for 15 seconds of Refrigerant Spray Application Time. Temperature (°C) of composite layer versus time (s) where temperature at -15 s represents the baseline temperature right before refrigerant spray application with a saturated cotton pellet. 0 s represents when the refrigerant spray saturated cotton pellet was removed from the bracket. The temperature was recorded every 5 s thereafter for 60 s. The test with refrigerant spray was repeated 5 times and the temperature recorded (Trial 1-5).

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Kumar V, Gossett L, Blattner A, Iwasaki LR, Williams K, Nickel JC. Comparison between Cone-Beam Computed Tomography and Intraoral Digital Radiography for Assessment of Tooth Root Lesions. *Am J Orthod Dentofacial Orthoped.* Jun 2011. 139(6): e533-41.