MEASUREMENT OF ORTHODONTIC BRACKET DEBONDING FORCE ON DIFFERENT TEETH USING A PROTOTYPE DEVICE EQUIPPED WITH FORCE SENSITIVE RESISTOR: AN IN-VITRO AND IN-VIVO STUDY

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LIST OF SYMBOLS AND ABBREVIATIONS

+	Plus
-	Minus
±	Plus Minus
×	Multiplication
/	Dividation
=	Equal
%	Percentage
°	Degree
>	Greater than
<	Less than
″	Inches
N	Newton Units of Force
KN	Kilo Newton
Mm	Millimeter
Nm	Nano-meter
M	Micro-meter
mm^2	Square millimeter
N/mm^2	Newton per square millimeter
cm^2	Square centimeter
G	Gram
Kg	Kilogram

MPa	Megapascal
V	Volt
R	Resistance
Kohm	Kilo-ohm unit of Resistance
P	Significance level
SEM	Scanning Electron Microscope
LODI	Lift-off Debonding Instrument
FSR	Force Sensitive Resistor
DFG	Digital Force Gauge
SEP	Self Etching Primer
RBC	Resin-Based Composite
GIC	Glass Ionomer Cement
RMGI	Resin Modified Glass Ionomer
APC	Adhesive Pre-coated
ADC	Analog to Digital Converter
UV	Ultraviolet
LED	Light Emitting Diode
VLC	Visible Light Curing
3D	Three Dimension
DSLR	Digital Single-lens Reflex
CMOS	Complementary Metal Oxide Semiconductor
IR	Infrared Reducing

SPSS	Statistical Package for the Social Sciences
ICC	Intraclass Correlation Coefficient
ANOVA	Analysis of Variance
USM	Universiti Sains Malaysia
PPSG	Pusat Pengajian Sains Pergigian
KPP	Klinik Pakar Pergigian
KRK	Klinik Rawatan Keluarga
JEPeM	Jawatankuasa Etika Penyelidikan (Manusia)

PENGUKURAN DAYA PENGYINGKIRAN PENDAKAP ORTODONTIK YANG GIGI BERBEZA YANG DILENGKAPI DENGAN KUASA PERINTANG SENSITIF: KAJIAN IN-VITRO DAN IN-VIVO

ABSTRAK

Kajian ikatan ortodontik harus diberi penekanan lebih lanjut untuk menguji kesan persekitaran oral terhadap pendakap ortodontik yang sentiasa berubah. Oleh itu, objektif kajian ini adalah untuk memperkenalkan prototaip yang mampu menyingkirkan pendakap ortodontik dengan daya puncak yang diperlukan, melalui mekanisma daya yang dikalibrasi. Sembilan puluh sembilan (99) sampel gigi dari rahang atas di sediakan untuk kajian in-vitro menggunakan 0.022 pendakap ortodontik (HKS 3, Ortho Classic, McMinnville, Amerika Syarikat), pelekat (Transbond XT dan Transbond Plus (3M Unitek, Monrovia, California, Amerika Syarikat) dan pengaktifan pencahayakan LED (model-DB686, COXO, Guangdong, China) selama 20 saat. Enam puluh (60) sampel dipilih untuk kajian pengesahan atau kalibrasi dan dibahagikan kepada dua kumpulan. Untuk ujian kebolehpercayaan sesama dan antara pemeriksa, tiga puluh sembilan (39) sampel dibahagikan kepada tiga kumpulan. Penyingkiran pendakap ortodontik dilakukan setelah dua puluh empat jam perlekatan dilakukan. Secara klinikal, daya penyingkiran pendakap ortodontik diukur pada 260 gigi yang berlainan untuk tiga belas (13) pesakit selepas rawatan ortodontik yang komprehensif dari gigi kacip sehingga gigi geraham kecil kedua untuk kedua-dua rahang atas dan bawah. Selepas penyingkiran dilakukan gambar intra-oral bagi setiap sampel gigi di ambil menggunakan mikroskop digital mudah alih untuk menilai corak kegagalan pendakap ortodontik dengan menggunakan skala 4-mata indek sisa pelekat (ARI). Analisis statistik yang digunakan adalah; ujian bebas t-tidak bergantung untuk kajian pengesahan, ujian koefisien korelasi intra-kelas untuk ujian kebolehpercayaan sesama dan antara pemeriksa, ujian ANOVA untuk membandingkan daya penyingkiran pendakap ortodontik antara gigi dan ujian Kruskall-Wallis bukan parametrik untuk membandingkan skala ARI antara jenis gigi yang berbeza. Secara klinikal tahap kepentingnya ditetapkan kurang daripada 0.05. Daya rata antara mesin uji universal (10.43 ± 2.71 N) dan peranti prototaip (9.36 ± 1.65 N) adalah tidak jauh berbeza ($p = 0.072$). Peranti prototaip mempamerkan nilai kebolehpercayaan yang sangat baik untuk sesama dan kedua-duanya pemeriksa (0.942 dan 0.921). Perbezaan ketara ($p < 0.001$) bagi penyingkiran purata antara jenis gigi yang berlainan secara klinikal dapat dilihat. Tiada perbezaan yang ketara ($p = 0.921$) untuk skor ARI diperhatikan secara klinikal di antara kumpulan gigi yang berbeza tetapi skor yang lebih tinggi adalah lebih banyak. Peranti prototaip ini adalah disyorkan untuk mengukur daya penyingkiran pendakap ortodontik secara klinikal sebagai peranti yang valid, terbukti dapat dipercayai dan menghasilkan kurang kerosakan pada permukaan gigi. Daya penyingkiran harus diukur pada gigi yang sama dari rahang yang sama kerana terdapat perbezaan yang ketara antara daya penyingkiran untuk gigi yang sama antara rahang atas dan bawah.

MEASUREMENT OF ORTHODONTIC BRACKET DEBONDING FORCE ON DIFFERENT TEETH USING A PROTOTYPE DEVICE EQUIPPED WITH FORCE SENSITIVE RESISTOR: AN IN-VITRO AND IN-VIVO STUDY

ABSTRACT

Orthodontic bonding studies should emphasize more on testing the effect of oral environment on the wide range of orthodontic bracket-adhesive systems that are evolving regularly. Therefore, the objective of this present study is to introduce a prototype device capable of debonding orthodontic brackets and measuring the peak debonding force clinically by a calibrated force sensor mechanism. Ninety-nine (99) maxillary premolar samples were prepared for the in-vitro studies. Standardized bonding protocol was maintained by a single clinician utilizing 0.022 metallic brackets (HKS 3, Ortho Classic, McMinnville, USA), Transbond XT adhesive with Transbond Plus self-etching primer (3M Unitek, Monrovia, California, USA) and LED light curing (model- DB686, COXO, Guangdong, China) for 20 seconds. Sixty (60) samples were divided equally into two (2) groups for the validation study. For intra and inter-examiner reliability, thirty-nine (39) samples were equally divided into three (3) groups. The brackets were debonded after twenty-four (24) hours of bonding. Clinically, orthodontic bracket debonding forces were measured on 260 different teeth in thirteen (13) patients after comprehensive fixed orthodontic treatment and divided equally into ten (10) groups from the central incisor to second premolar. Following debonding procedure, intra-oral micro-photograph of each tooth was taken using portable digital microscope for assessing the bracket-failure pattern by 4-point scale of adhesive remnant index (ARI). Statistical analysis included-independent samples t-test for validation study, intraclass correlation coefficient test for intra and inter-examiner reliability, one-way ANOVA to compare in-vivo mean debonding forces between different tooth groups and the non-parametric Kruskal-Wallis test to compare in-vivo ARI between different tooth types. The significance level was set at less than 0.05. The mean debonding force between the universal testing machine (10.43 ± 2.71 N) and the prototype device (9.36 ± 1.65 N) was not significantly different ($p = 0.072$). The prototype device exhibited excellent intra and inter-examiner reliability (0.942 and 0.921). Significant difference ($p < 0.001$) of mean debonding force was found between different types of teeth in-vivo. Clinically, ARI scores were not significantly different ($p = 0.921$) between different groups but overall higher scores were predominant. The prototype device can be recommended for measuring clinical bracket debonding force as the device is validated, proved to be reliable and based on clinical ARI scoring caused less iatrogenic enamel damage. Bracket debonding force should be measured on same tooth from the same arch as significant difference of mean debonding force exists between similar teeth of the upper and lower arches.

CHAPTER ONE

INTRODUCTION

1.1 Background of the study

Orthodontic brackets are an integral part of the fixed orthodontic appliance bonded either directly or indirectly to the prepared teeth surface by the means of various adhesives. Through the brackets, the force generated by the activated archwires are transmitted to the teeth and the prescribed biomechanical tooth movements are performed to correct different types of malocclusion. To ensure the consistency and success of such an expensive and laborious treatment protocol, it is important to prevent unwanted bracket failure during the course of treatment. Thus, bonding of orthodontic brackets to the teeth have been studied extensively to produce and maintain a stable interface between the bracket-adhesive and as well as between the adhesive-tooth enamel.

Assessments on the performance of the wide range of orthodontic bonding systems were predominantly done- either by the in-vitro or ex-vivo bond strength studies or by the analysis of the site and the rate of clinical bracket failure throughout the treatment period. Conducting studies that focus on the clinical bracket failure rates under a controlled environment such as- identical situations in terms of malocclusion, appliance prescription, force application and status of the patient are laborious and requires prolonged monitoring (Eliades and Brantley, 2000). On the other hand, bond strength studies relying on the laboratory-based mechanical tests, apply either true shear or tensile force by the universal testing machine on the bracket until debonding. By these tests, certain features of the physical and chemical adhesive properties can be explained but the actual performance of a material should only be tested where it is intended to function (Eliades and Brantley, 2000). Prolonged exposure to the oral environment causes the dental materials to be degraded by dissolution in saliva, stress from the activated archwire, forces of mastication, variation in the temperature and pH, bacteria and their by-products (Eliades and Brantley, 2000; Øilo, 1992). Due to the biodegradation, studies found that bond strength of the orthodontic brackets is lower in-vivo than in-vitro (Hajrassie and Khier, 2007; Murray and Hobson, 2003; Penido *et al.*, 2009; Pickett *et al.*, 2001).

The universal testing machine is considered ‘gold-standard’ for its accuracy and precision but due to its dimension, yet not possible to introduce clinically. Besides, the machine cannot precisely reproduce the mechanics of clinical bracket failure. Because the machine can apply either true shear or tensile force on the bracket at much lower impact velocity than in clinical situations of debonding (Eliades and Brantley, 2000). Brackets are exposed to the combined shear-peel, tension and torsional loading modes during the course of treatment as well as during clinical debonding (Katona, 1997). Murray and Hobson, (2003) constructed a special removable appliance made of enamel slabs bonded with brackets to test the bond strength in the oral environment. After exposing the brackets to the oral environment for a certain period, the appliance was retrieved and the bond strength was tested in the laboratory. Eliades and Brantley, (2000) stressed the importance of constructing a debonding device which will apply loads in a standardized manner according to the manufacturer’s direction while providing a quantitative measure of the applied force. In response to that statement, modified debonding devices were constructed and the bond strength of the orthodontic brackets were tested in the oral environment

(Brosh *et al.*, 2005; Hajrassie and Khier, 2007; Hassan, 2010; Hildebrand *et al.*, 2007; Penido *et al.*, 2009; Pickett *et al.*, 2001; Prietsch *et al.*, 2007; Tonus *et al.*, 2017). These devices were either modified elastic spacer instrument with a digital force gauge (DFG) or debonding pliers attached with strain gauge at the handles. Debonding by the elastic spacer instrument and DFG is more complex, as, in all instances, the subjects were given acrylic splints to prevent enamel damage (Hajrassie and Khier, 2007; Hassan, 2010; Penido *et al.*, 2009; Pickett *et al.*, 2001; Tonus *et al.*, 2017). The pattern of bracket failure or the extent of enamel damage by this device is still unknown. On the other hand, strain-gauge results are solely based on the deformation of the object to which it is attached. Therefore, in debonding devices equipped with strain-gauge, the force values obtained were the measure of the deformation of the plier handles where the strain-gauge was attached. Hence, the results can be influenced by the variation in the type of debonding plier and the manner in which they are held (Tonus *et al.*, 2017).

Variation in the debonding force or the bond strength of the orthodontic brackets according to the tooth types were emphasized previously in only three in-vitro studies (Hobson *et al.*, 2001; Linklater and Gordon, 2001; Öztürk *et al.*, 2008). In contrast, the majority of the in-vitro and in-vivo studies considered the bond strength of orthodontic brackets on the premolar teeth to be representative of all tooth types. Some studies used upper and lower teeth of the same type in one group (Bishara *et al.*, 1998; Büyükyilmaz *et al.*, 1995; Katona, 1997). Clinically, only one study found to measure orthodontic bond strength on different tooth groups but only limited to the upper arch (Hassan, 2010).

1.2 Gap statement

To overcome the limitation of the previous experimental debonding devices designed to measure orthodontic bracket debonding force in-vivo, the current study introduced a prototype device equipped with force sensitive resistor (FSR). This is a novel method of measuring orthodontic bracket debonding force since no study found in the literature to measure bracket debonding force utilizing FSR. FSRs are thin, light-weight, dynamic, durable, inexpensive, easier to install and depends on the direct force application. Previously in dental research, FSR was used to measure bite force with 93% reliability (Fernandes *et al.*, 2003). To justify the application in clinical situations, the study aimed to confirm the validation and both inter and intra-examiner reliability of the prototype device as the validation and reliability of some of the previous devices were not mentioned (Brosh *et al.*, 2005; Hildebrand *et al.*, 2007). Also, in light of the previous in-vitro studies, the current study was focused on establishing a clinical data on the orthodontic bracket debonding force specific to different types of the tooth in both upper and lower arch. Finally, following the debonding procedure by the prototype device, the study intended to assess the bracket failure pattern or the extent of enamel damage clinically respective to different tooth types by a four (4) point scale of adhesive remnant index (ARI). This was done to check the consistency of the bracket failure pattern respective to the tooth types by the prototype in terms of enamel damage which was not observed in previous in-vivo studies.

1.3 Objectives of the study

1.3.1 General objective

To introduce a prototype orthodontic bracket debonding device equipped with force sensitive resistor (FSR) capable of measuring orthodontic bracket debonding force both in-vitro and in-vivo.

1.3.2 Specific objectives

i. To compare the mean debonding force values between the universal testing machine and the prototype device.
ii. To compare the orthodontic bracket debonding force clinically between different teeth (central incisor to the second premolar) from both sides of the upper and lower arch.
iii. To compare the orthodontic bracket failure pattern clinically between different teeth according to the adhesive remnant index (ARI).

1.3.3 Research questions

i. Is the prototype device comparable and an alternative to the ‘gold standard’ universal testing machine for measuring orthodontic bracket debonding force?
ii. Is the prototype orthodontic bracket debonding device consistent and reliable irrespective of the examiners?
iii. Is there any significant difference of mean orthodontic bracket debonding force between different tooth types clinically in both upper and lower arch?

iv. Is there any significant difference in bracket failure pattern or adhesive remnant index (ARI) scoring clinically between different tooth types?

v. Is the prototype device safe or limiting damage to the surface enamel during debonding orthodontic brackets?

1.3.4 Research hypothesis (Alternate hypothesis)

i. The prototype device is comparable to the universal testing machine for measuring orthodontic bracket debonding force and can be used as an alternative.

ii. The prototype device is reliable irrespective of the examiners.

iii. There is a significant difference in mean orthodontic bracket debonding force between different teeth groups clinically in both upper and lower arch.

iv. There is a significant difference in bracket failure pattern or ARI score clinically between different teeth.

v. The prototype device is safe as it conserves the surface enamel during debonding orthodontic brackets.

CHAPTER TWO

LITERATURE REVIEW

2.1 Structure, composition and characteristics of enamel:

The tooth consists of a hard, inert, acellular enamel formed by the epithelial cells which are supported underneath by more resilient, less mineralized but vital hard connective tissue called dentin. The dentin is formed and supported by a soft connective tissue called dental pulp.

Enamel is the hardest calcified tissue of the body, consisting of more than 96% inorganic components and traces of organic material with water. The main inorganic component of enamel is the crystalline calcium phosphate (hydroxyapatite). Enamel is translucent and varies in thickness with the maximum of approximately 2.5 mm over the working surfaces to a feather edge at the cervical line. The basic structural units of enamel are the enamel rods (prisms) and inter-rod enamel made of hydroxyapatite crystals which are closely packed and differentiated. The rods are cylindrical in shape and directed longitudinally. There is a narrow space containing organic material in between the rod and inter-rod enamel, known as rod sheath (Nanci, 2012).

The high mineral content with complex structural organization enables enamel to withstand functional forces but that also make enamel more brittle for which it relies on the underlying layer of more resilient dentine to maintain its functional integrity.

2.2 Orthodontic brackets and the fixed orthodontic appliances:

Brackets are the devices usually made of metals (e.g. stainless-steel, gold or titanium), ceramics, or plastics (Zachrisson and Büyükyilmaz, 2012) that are bonded either directly or indirectly on to the teeth surface by various adhesives. These brackets are equipped with arch wires and the force generated by these activated arch wires are transferred to the teeth through the brackets in order to facilitate the teeth movement. In the year of 1916, the father of modern orthodontics Dr. Edward Angle constructed an orthodontic appliance capable of exerting force in two dimensions very lightly and continuously with a good control (Green, 2014). This was a ribbon arch appliance containing delicate metallic devices welded to the bands. These metallic devices were named 'Brackets' by Dr. Angle himself. Based on this theory, Dr. Angle made further progress and introduced the famous 'edgewise system' in 1928 which could move all the teeth three-dimensionally except rotation and considered to be the foundation of the modern fixed orthodontic appliance therapy (Sinha and Nanda, 2001). In that appliance, all the brackets bonded to the teeth were similar, rectangular arch wires were fitted to the bracket slots and the teeth movements were facilitated by adding bends to the arch wires (Sinha and Nanda, 2001). In 1920s Dr. PR. Begg, a student from the Angle's school modified the ribbon arch appliance and invented another appliance named as the 'Begg system' which is also known as the differential force system. Instead of precious metal ribbon arch, Begg used light, round stainless-steel arch wires inside the modified ribbon arch brackets which were placed gingivally (Vertical Slots) (Proffit *et al.*, 2013). For so many years, these two appliance systems were used by the clinicians with one or two modification for desirable use. The brackets were similar for all the teeth in both appliance systems. However, it was not until the 1980s, when Dr. Lawrence Andrews introduced the straight wire appliances where each bracket was made tooth specific with built-in torque, tip, and in/out (Secchi and Ayala, 2011). Hence, eliminating the need for repetitive bends in the arch wire in order to counteract the differences in the tooth anatomy (Proffit *et al.*, 2013). In this appliance system, each bracket was contoured mesiodistally and occluso-gingivally following the curvatures on the labial surface of each tooth for achieving optimal bonding (Secchi and Ayala, 2011).

2.2.1. Orthodontic Bracket Designs:

2.2.1(a) Metal Brackets:

The first introduced metal brackets were made of stainless-steel. It had rough perforated bases for allowing the flow of the adhesives (Sheykholeslam and Brandt, 1977). These stainless-steel brackets adhere with the adhesives by the means of mechanical interlocking at the bracket base-adhesive interface, not by chemical bonding (Ferguson *et al.*, 1984). For mechanical interlocking, the bracket base had only one row of perforations around the periphery with the larger inner smooth surface, not contributing to the retention. For this reason, this base design was later developed into foil-mesh bracket base which exhibited higher bond strength (Ferguson *et al.*, 1984; Lopez, 1980) and less plaque accumulation (Maijer and Smith, 1981). But as these foil meshes were welded to the bracket bases, the electron microscopy revealed that the weld spots are unretentive, contribute to stress concentrations in the adjacent adhesive and thus lower the bond strength (Maijer and Smith, 1981). Moreover, the flexible pads of the foil-mesh bracket bases readily distort and bend away from the tooth surface causing soft tissue injury and complicating the mechanical retention (Reynolds and Von Fraunhofer, 1977). Also during debonding, some parts of the foil-mesh have a tendency to separate, leaving the remnants of the wire-mesh on the tooth surface (Moin and Dogon, 1978). Welding was replaced by brazing as a method of attaching the foil-mesh to the bracket base to prevent its distortion (Richardson, 2010).

Conflicting reports have been found regarding the influence of variation on the pattern of the bracket base morphology to the overall bond strength. Reynolds and von Fraunhofer (1977) reported that coarse mesh improves the bond strength. On the other hand, Maijer and Smith (1981) stated that the bracket base with fine woven mesh promotes the bond strength. Another study, investigated the effect of variation in the surface morphology of bracket base and orthodontic adhesive on the bond strength and concluded that, the orthodontic adhesive had the greater influence on the bond strength although, specific base design may facilitate improved penetration of the orthodontic adhesives and curing light (Knox *et al.*, 2000). Also, Bishara *et al.* (2004) found no difference of shear bond strength and bracket failure pattern between the single mesh and double mesh metallic bracket base using the same orthodontic adhesive.

2.2.1(b) Plastic brackets:

In the early 1970s, the plastic brackets were commercially introduced. They were made of polycarbonate. Although they were used mainly for aesthetic reasons as an alternative to the metallic brackets, their popularity was short-lived due to major disadvantages like- staining and odors, lack of strength and stiffness, tie wing fractures and permanent deformation (Aird and Durning, 1987). Such brackets may be indicated in cases of short duration with lower force requirements because under constant stress the bracket slots distort with time (Dobrin *et al.*, 1975; Zachrisson and Büyükyilmaz, 2012). There was also higher torque loses and lower torquing moments found with polycarbonate brackets in comparison to the metallic brackets (Harzer *et al.*, 2004).

High-grade polyurethane brackets and polycarbonate brackets reinforced with metal slots and ceramic and fiberglass fillers were introduced to improve the strength and rigidity but the torque problem still persists (Richardson, 2010).

2.2.1(c) Ceramic brackets:

With the advantages of higher strength, creep and wear resistance, better color stability and aesthetics ceramic brackets were commercially available during the 1980s (Richardson, 2010). Chemically ceramic brackets are a monocrystalline or polycrystalline form of aluminum oxide. They bond to the enamel either by the mechanical interlocking with the help of indentations or undercuts at their bases or chemically via a silane-coupling agent (Zachrisson and Büyükyilmaz, 2012). Ceramic brackets relying on the mechanical retention with chemically or light cured adhesives are mostly preferred because the chemical bonding resulted in enamel damage during debonding due to excessive bond strength (Russell, 2005). The debonding characteristics of the metal and mechanically retained ceramic brackets were also found similar (Habibi *et al.*, 2007). But, in comparison to metal brackets, ceramic brackets have many drawbacks like- higher frictional resistance between the wire and the slot (Omana, 1992), more brittle (Gibbs, 1992), harder than steel, inducing enamel wear of the opposing teeth in contact (Douglass, 1989); more susceptible to wing fracture during debonding, accumulates more plaque and staining due to rougher surface (Zachrisson and Büyükyilmaz, 2012).

2.2.1(d) Adhesive pre-coated brackets:

Adhesive pre-coated brackets (APC) were mainly introduced with the aim of reducing chairside time clinically by the faster and easier bonding steps. They are available in both metallic and ceramic versions since 1991. The pre-coated adhesive is the modified Transbond XT (3M Unitek, California, USA) composite with an increased viscosity which can be used with Transbond Plus Self-Etching Primer (Richardson, 2010). Other than reducing chairside time, the following advantages were noted with adhesive pre-coated brackets: consistency in the quality and quantity of the adhesive, easy to clean-up excess adhesive after bonding, less wastage, better infection and inventory control (Richardson, 2010).

Bishara *et al.* (1997), evaluating the in-vitro shear bond strength of adhesive pre-coated metallic brackets, found lower bond strength in APC brackets compared to non-APC brackets. The increased viscosity of the pre-coated adhesive in combination with the mesh retention mechanism of the metallic bracket base were responsible for lowering the shear bond strength. In response to that finding, manufacturers modified the viscosity of the pre-coated adhesive and introduced APC2 (Richardson, 2010).

Similarly, Cal-Neto *et al.* (2006) also reported lower shear bond strength in APC metallic brackets. The shear bond strength of APC brackets was also found lower in an in-vivo study compared to conventional brackets (Hassan, 2010).

2.3 Bonding Orthodontic Brackets:

Orthodontic brackets can be bonded to the teeth either by direct or indirect technique. In both techniques, the common steps involved are- cleaning, enamel conditioning, sealing and bonding (Zachrisson and Büyükyilmaz, 2012). Before this concept, brackets were attached to the teeth with the help of metallic bands. But not after 1965 when Newman successfully bonded the brackets directly to the teeth surface by using epoxy adhesive system (Newman, 1965). In direct bonding, brackets are directly positioned on the prepared teeth surface intraorally. The common challenge faced by the clinicians during direct bonding is the accurate positioning of the brackets. But on the other hand, direct bonding is faster, easier and less expensive in comparison to the indirect bonding (Proffit *et al.*, 2013). The indirect method of bonding orthodontic brackets was introduced shortly in 1972 when brackets were first bonded on the study model with water-soluble adhesive and then transferred to the teeth with help of a custom tray (Silverman *et al.*, 1972). Now, brackets are bonded to the patients' study model with the filled resins. After that, the unfilled liquid sealant is applied to the prepared teeth surface, the brackets are transferred into the mouth using custom-tray made of vinyl-polysiloxane putty and the tray is carefully removed after bonding between the pre-cured resin at the bracket base and the unfilled liquid sealant on the teeth surface (Sinha and Nanda, 2001). The advantages of indirect bonding are- the brackets can be located more precisely than in direct technique because the bracket bonding can be examined from all angles without any hindrances from the cheeks and saliva (Proffit *et al.*, 2013), the thickness of adhesives between the brackets and the teeth surface can be better controlled, easier debonding and patient comfort due to reduced chairside time. The disadvantages of indirect bonding are- complex and technique sensitive procedure, expensive because of the laboratory procedures (Sinha and Nanda, 2001). Despite the difference in procedure, the shear bond strength between the directly and indirectly bonded orthodontic brackets was not different (Gia *et al.*, 2003).

2.4 Tooth surface preparation for bonding orthodontic brackets:

2.4.1 Tooth Prophylaxis:

Prior to acid etching, it is necessary to clean the surface enamel of the in-vitro tooth samples for allowing easier penetration of the etchant into the enamel. Because the enamel surface of the tooth samples is covered with pellicle formed by the selective binding of glycoproteins from the saliva (Richardson, 2010).

Most commonly, tooth prophylaxis is done by using abrasives like pumice, silica or zirconium silicate on a bristle brush or rubber cup with the slow-speed rotatory device.

In the present study, prophylaxis of the tooth samples was done by using pumice paste on the bristle-brush attached to a slow-speed handpiece. However, in previous studies, prophylaxis with pumice had no significant influence on the bond strength of orthodontic brackets (Bishara *et al.*, 1996; Lindauer *et al.*, 1997). Although, scanning electron microscopy revealed attached plaque and debris on the unpumiced tooth surface after etching (Lindauer *et al.*, 1997). Another study reported that the clinical failure rates of the orthodontic brackets were significantly reduced when the surface conditioning was done by the self-etching primer (SEP) after pumice prophylaxis (Lill *et al.*, 2008).

2.4.2 Acid etching:

Buonocore's idea of acid etching the enamel was mainly originated from the observation of treating the metal surface with phosphoric acid to obtain better adhesion to the paint and resin coatings in industries (Buonocore, 1955). He treated the enamel surface with 85% phosphoric acid for 30 seconds and found improved adhesion of the acrylic filling material. After that in a study, electron microscopy first revealed that micropores created by the acid etching in the enamel structure allowed the adhesives to penetrate and establish mechanical bonding after polymerization (Gwinnett and Matsui, 1967). Later, Buonocore *et al*. (1968) also identified the formation of microscopic resin tags and their penetration into the etched enamel structure for adhesion which is the basis of micro-mechanical retention.

Scanning electron microscopic (SEM) analyses were done to investigate the pattern of etching on the enamel surface (Bhad and Hazarey, 1995; Galil and Wright, 1979; Silverstone *et al.*, 1975). Silverstone *et al.* (1975) first classified etching pattern into three (3) types: preferential removal of the enamel prism core with intact periphery (Type 1), removal of the peripheral zones of the prisms with unaffected prism cores (Type 2), areas corresponding to both Type 1 and Type 2 (Type 3). Later, Galil and Wright, (1979) modified the classification by adding two more types: pitted enamel surface (Type 4), smooth and flat enamel surface after etching (Type 5). Type 1 and 2 were mainly located on the coronal third of the buccal surface, Type 3 on the middle third and the cervical areas mostly exhibited Type 4 and 5 (Galil and Wright, 1979). Maximum enamel damage occurs in Type 2 and minimum in Type 1 (Bhad and Hazarey, 1995).

For bonding orthodontic brackets, different concentrations of phosphoric acid and different etching times were experimented to observe the overall impact on the bond strength and enamel damage. Legler *et al.* (1989) exposed the tooth samples to the phosphoric acid etchant at different concentrations (5%, 15%, and 37%) for different duration of time and found that the duration of etching, not the acid concentration influenced the shear bond strength. Bhad and Hazarey, (1995) also achieved the similar shear bond strength of orthodontic brackets between the tooth samples treated with 5% and 37% phosphoric acids, but observed minimal enamel damage in the samples treated with 5% acid under the scanning electron microscope (SEM). Sheen *et al.* (1993) found no significant difference in bond strength between younger and older permanent teeth with etching durations of 15 and 60 seconds. That study also recommended 15 seconds as the optimal etching time for both young and permanent teeth as a preventive of enamel damage. Alternately, Wang *et al.* (1994) found a significant difference in bond strength between the tooth samples treated with different concentrations of phosphoric acid from 2% to 80%. That study found the highest bond strength in the groups treated with 10% to 60% phosphoric acid concentrations while the lowest bond strength in the groups treated with 2% and 80%. Clinically, to achieve greater bond strength with less enamel damage that study also recommended the phosphoric acid concentrations to be 10% to 30% for 15 seconds.

2.4.3 Self-etching primer:

Self-etching primers (SEPs) were introduced with the aim of improving chairside time and cost-effectiveness by converting surface conditioning and priming into a single step. The principal ingredient of the SEPs is a methacrylate phosphoric acid ester that dissolves calcium from the hydroxyapatite. The dissolved calcium instead of being rinsed away forms a complex and is incorporated into the network when the primer polymerizes. Here, etching and penetration of the monomer into the exposed enamel prisms occur simultaneously. The depth of etching and primer penetration are also similar (Zachrisson and Büyükyilmaz, 2012).

In the present study, Transbond Plus (3M Unitek, California, USA) self-etching primer was applied to both in-vitro and in-vivo teeth samples. It is available in a single pack of three compartments. The first compartment contains methacrylate phosphoric acid esters with photosensitizers and stabilizers. The second compartment contains water and soluble fluoride and the third compartment contains an applicator brush. Activation of the components is done by squeezing and folding the first compartment into second. Then the activated solution is rubbed thoroughly with the brush on the tooth surface for at least three (3) seconds.

In comparison to conventional acid etching, surface preparation with SEPs exhibited significantly lower but clinically acceptable shear bond strength (Bishara *et al.*, 2001). That study also reported- in SEP group bracket failure mostly occurred at the bracket-adhesive interface which prevented enamel damage.

Other than improving time and cost-effectiveness, manufacturers also claimed the ability of the SEPs to work efficiently in the moist environment. Cacciafesta *et al.* (2003) found that in the presence of water and salivary contamination SEPs exhibited higher bond strength compared to hydrophilic and conventional primers.

However, Dorminey *et al.* (2003) stressed the importance of air dispersion after applying a self-etching primer on the tooth surface. Omitting air dispersion after applying SEPs significantly reduced the shear bond strength than the other two test groups- SEP with air dispersion and conventional two-step bonding. Also, for effective bonding, SEPs rely on the cleaning of the enamel surface with pumice prophylaxis which can be skipped during conventional two-step bonding (Ireland *et al.*, 2003; Lill *et al.*, 2008).

2.5 Orthodontic Adhesives:

2.5.1 Resin-based composites (RBCs):

Resin-based composites are composed of three (3) basic elements: highly cross-linked polymeric resin matrix reinforced by the dispersion of the glass, mineral or resin filler particles which is bound to the resin matrix by the coupling agent (Anusavice *et al.*, 2013). Two basic types of resins used for orthodontic bracket bonding: acrylic and diacrylate resins existing in both filled and unfilled forms. Acrylic resins are a methyl-methacrylate monomer and the diacrylate resins are acrylic modified epoxy resin bisphenol-A glycidyl dimethacrylate (bis-GMA) or Bowen’s resin (Bowen, 1979). Bowen’s resin polymerized by cross-linking into a three-dimensional network providing improved physical properties. The filled variety of this resin type is the strongest adhesive for metal brackets with best physical properties (Zachrisson and Büyükyilmaz, 2012).

Polymerization of the resin-based composites can be done by the chemical activation, light activation or combination of light and chemical activation (dual-cured resins) (Ewoldsen and Demke, 2001). Chemically activated resins contain two-paste systems which require mixing to initiate the polymerization. The problems encountered with chemical activated resins are: entrapment of air into the mix that weakens the structure and inhibits polymerization, the operator has no control over the working time (Anusavice *et al.*, 2013). Clinical bonding procedure was simplified with the introduction of no-mix adhesive. Here, one component of the adhesive is applied to the bracket base and the other on the etched enamel. After precise positioning of the bracket, it is firmly held in position with light pressure until the completion of polymerization usually within 30-60 seconds (Zachrisson and Büyükyilmaz, 2012). The average bond failure rate of no-mix adhesives was found 7.2% which is clinically acceptable (Adolfsson *et al.*, 2002). The light cured resins are most popular among the orthodontists for allowing more precise positioning of the brackets within an extended working time. Light cured resin adhesives are supplied as a single paste with photosensitizer and initiator in a lightproof syringe. In comparison to chemical cured adhesives, light-cured resins exhibited lower but acceptable bond strength (Toledano *et al.*, 2003) and similar clinical failure rates (Galindo *et al.*, 1998; O'brien *et al.*, 1989). Dual cured resins do not require acid etching and thus prevent iatrogenic loss of enamel which is between 10 to 30 µm. They can bond chemically to the enamel, dentine, metal, ceramic and composite but the bond strength was found lower than the light-cured resins. (Vicente *et al.*, 2005).

Fluoride is also incorporated into the adhesive resins to fight against the formation of white spot lesions around the orthodontic bracket and adhesive. Fluoride-containing adhesive resins have shown to decrease enamel decalcification in patients with fixed orthodontic appliances (Wilson and Donly, 2001).

2.5.2 Glass ionomer cement:

Glass ionomer cement (GICs) was introduced in 1972 with the unique properties like- chemically bonding to enamel and dentin, the ability to release fluoride to prevent dental caries (Wilson, 1972). Traditionally, it has two components: powder and liquid. The powder contains a glass of calcium, fluoride, alumina, and silica; liquid contains an aqueous solution of polyacrylic acid (Anusavice *et al.*, 2013). Despite having the unique properties, several drawbacks were noted in glass ionomers like- extended setting time, high viscosity, technique sensitivity and inferior esthetics. For these reasons, modifications like- incorporation of polyacrylic acid into the powder component by freeze drying and tartaric acid into the liquid led to the introduction of a second-generation or water hardening glass-ionomer with less viscosity and shorter setting time (Klockowski *et al.*, 1989).

In the field of orthodontics, initially, glass ionomer cement was used for bonding bands as a better alternative to zinc phosphate and zinc polycarboxylate cement because of greater physical properties, less decalcification and adhesion to the enamel and dentine (Zachrisson and Büyükyilmaz, 2012). Researchers then emphasized the importance of using glass ionomer as an orthodontic adhesive for bonding brackets and preventing decalcification around it at the same time. Glass ionomer cement exhibited good potentiality for controlling decalcification (Marcusson *et al.*, 1997) but the bond strengths were found lower in comparison to the resin adhesives (Bishara *et al.*, 1999; Klockowski *et al.*, 1989; Rezk-Lega and Øgaard, 1991). Also, the high clinical failure rate of 20% reported when the brackets were bonded with glass ionomer (Fricker, 1992).

To improve the bond strength as an orthodontic adhesive, the methacrylate-based monomer was incorporated into the liquid component of glass ionomer. This modified version of glass ionomer is also known as resin-modified glass ionomer (RMGI) or hybrid ionomer cement. The resin can be polymerized by the light activation, chemical activation or both (Anusavice *et al.*, 2013). The light curing version of RMGI allows rapid setting, reducing the sensitivity of the material to the moisture. Komori and Ishikawa, (1997) found that both tensile and the shear bond strength of RMGI were greater than the conventional glass ionomer. In comparison to resin adhesive, RMGI exhibited significantly lower but clinically acceptable bond strength and similar in-vivo bracket survival rates after 1.3 years (Summers *et al.*, 2004). But when enamel was conditioned with 37% phosphoric acid RMGI had similar shear bond strength compared to resin adhesive (Godoy-Bezerra *et al.*, 2006). Cacciafesta *et al.,* (2003) recommended enamel conditioning preferably with self-etching primer before using RMGI to achieve better bond strength.

2.5.3 Polyacid modified composite:

To integrate the fluoride-releasing capacity of glass ionomer and durability of composite resins, polyacid-modified composite or compomer is introduced. Compomer is made by incorporating the glass particles of GIC in water-free polyacid liquid monomer with an appropriate initiator (Anusavice *et al.*, 2013). The duration and amount of fluoride-releasing capacity of compomer were found lower in comparison to RMGI (Rix *et al.*, 2001a). Unlike GIC or RMGI, compomer requires dentin bonding agent prior to the application. Many studies were conducted to evaluate its effectiveness as an orthodontic adhesive (Chitnis *et al.*, 2006; Millett *et al.*, 1999; Rix *et al.*, 2001b; Rock and Abdullah, 1997). Other than Millett *et al.* (1999), the mean bond strength of compomer was found significantly lower in comparison to conventional resin adhesive and RMGI. However, in a comparative clinical trial, extending over the full course of treatment, brackets bonded with compomer and resin adhesive had the similar failure rates (Millett *et al.*, 2000).

2.6 Light curing units:

Light cured adhesives are most popular among orthodontists due to the advantages like-reduced risk of contamination, more accurate bracket placement and reduced chairside time. Initially, ultraviolet (UV) light source was used for curing adhesive resins which were capable of curing one millimeter of resin per minute. Because of the safety concerns with the long-term use of UV light, visible light curing (VLC) unit was introduced. The light source of VLC is tungsten-halogen which also have greater depth of curing than the UV light. Camphorquinone is added in the adhesives which act as a photosensitizer to VLC unit at 470 nm wavelength spectrum. According to the manufacturers, VLC units can cure conventional composite resins in 20 seconds and RMGIs in 40 seconds for each bracket (Sfondrini *et al.*, 2001). This prolonged curing time was inconvenient for the clinicians. Improvements were made by introducing fast halogens (e.g., Optilux 501, Kerr, USA) with higher intensity output to reduce the curing times to half of the time needed with conventional VLC units (Zachrisson and Büyükyilmaz, 2012). In the late 1980s, argon lasers were introduced. Around 480 nm wavelength spectrum, argon lasers were capable of reducing the curing times for unfilled resins to five (5) seconds and filled resins to 10 seconds (Sfondrini *et al.*, 2001). However, due to the high cost and lack of portability, their use in orthodontics is not extensive (Zachrisson and Büyükyilmaz, 2012). In the mid-1990s, the xenon plasma arc lamp was introduced for high-intensity curing. The lamp consists of a tungsten anode and a cathode in a quartz tube filled with xenon gas. As the electricity passes through the xenon gas, it becomes ionized and forms plasma made up of positively and negatively charged particles and generates intense white light (Zachrisson and Büyükyilmaz, 2012). For bonding orthodontic brackets, curing of orthodontic adhesives with plasma arc lamp compared to VLC unit is advantageous as it reduced the curing time in both resin adhesive and RMGI to two (2) seconds without affecting the shear bond strength (Sfondrini *et al.*, 2001). Also, no significant difference in failure rates was noted between brackets cured with halogen light for 20 seconds and plasma arc light for five (5) seconds (Sfondrini *et al.*, 2004). But the plasma arc lamps are more expensive than halogen-based visible light. Also, halogen light curing unit has many disadvantages like- high power consumption, short working lifespan (approximately 40-100 hours), degradation of the light filter with time, sensitivity to the shock and vibration (Üşümez *et al.*, 2004). To overcome the limitations of the VLC unit, Mills (1995) proposed the use of a solid-state light emitting diode (LED) for curing light activated dental materials. LEDs have a longer lifespan (approximately 10,000 hours), consume less electricity, cordless, inexpensive, no filters require, shock and vibration proof. Curing of orthodontic adhesives with LED unit for 20 seconds produced shear bond strength comparable to those cured with halogen light for 40 seconds (Üşümez *et al.*, 2004). Similar failure rates between the brackets bonded by LED curing for 10 seconds and halogen light for 40 seconds were noticed after a 15-month clinical trial (Krishnaswamy and Sunitha, 2007). Di Nicoló *et al.*, (2010) suggested that, curing adhesive precoated brackets for 10 seconds with LED reduce chairside time without affecting the bond strength.

Bishara *et al.* (2003) stated that, by using second-generation LED units, clinicians can cure two orthodontic brackets at a time with the same light exposure without affecting the shear bond strength. Hence, the chairside time can be reduced to half. Also, no significant difference of bond strength found in the brackets cured with the second generation LED at a distance of 1 and 10 mm (Gronberg *et al.*, 2006).

2.7 Tooth samples:

To date, the orthodontic bracket debonding force was principally measured either on the bovine incisors or on the extracted human teeth. Oesterle *et al.*, (1998) reported that the shear bond strength of orthodontic brackets on bovine enamel was found significantly weaker (21% to 44%) in comparison to human enamel. Saleh and Taymour, (2003) also found significantly lower shear and tensile bond strength of bovine enamel. The weaker bond strength may due to larger crystal grains and more lattice defects than human enamel contributing to lower surface tension. For ex-vivo bonding studies, sound premolar tooth is more easily obtainable due to extraction for orthodontic reasons, but the variation of surface curvatures in premolars complicates to achieve substrate surface consistency (Eliades and Brantley, 2000). Besides, bond strength results, obtained from the premolar tooth samples, are not representative of all tooth types. Many in-vitro studies found a significant difference in the bond strength between different tooth types (Hobson *et al.*, 2001; Linklater and Gordon, 2001; Öztürk *et al.*, 2008). In-vivo brackets failure rates were also found greater on the posterior teeth than the anterior (Linklater and Gordon, 2003). But in-vivo bracket failure rates do not correlate with the ex-vivo bond strength (Linklater and Gordon, 2003) and yet, no study is conducted to measure and compare orthodontic