In Vitro Investigation into Bond Strength of Metal and Ceramic Orthodontic Brackets

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Abstract

Aims

The aims of this study were:

1. To determine *in vitro* bond strength of metal and ceramic orthodontic brackets when bonded using etch and a separate primer, or a self-etching primer (SEP).
2. To assess remaining adhesive following removal of orthodontic brackets

Null Hypotheses

- There is no difference in shear bond strength between metal and ceramic brackets when removed using a standardized *in vitro* debonding technique.
- There is no difference in adhesive remaining following debonding of metal and ceramic brackets.

Method

One hundred and eighty previously extracted human premolar teeth were randomly allocated to one of six test groups. Specimen teeth were mounted in cold-cure acrylic and brass tubes. Each was subjected to enamel surface preparation using either 37% phosphoric acid gel, followed by application of 3M Unitek Transbond© Plus, or by means of a self etching primer (3M Unitek Transbond© Plus SEP). Orthodontic brackets were bonded to the prepared

enamel surface and light cured, following the manufacturers guidelines. The brackets used were 3M Unitek Victory© series metal, Clarity© metal reinforced ceramic and Transcend© all-ceramic brackets.

Specimens were stored at 37° for 24 hours following bonding. Each was then subjected to bracket removal using the Instron Universal testing machine, measuring shear bond strength for each sample.

Specimens were then examined under x10 magnification light microscopy and allocated an Adhesive Remnant Index (ARI) score (Årtun and Bergland, 1984).

Results

Variations in mean shear bond strength were found between all test groups. The lowest bond strength was Group 2, Victory© series brackets bonded with SEP with bond strength of 7.08 MegaPascals (MPa). The highest shear bond strength was Group 3, Clarity© series brackets bonded with etch and primer, where the mean bond strength was 15.96 MPa. Pooled data showed that significantly higher bond strengths were produced with etch and primer than SEP ($T = 2.83$, $p < 0.01$).

Correlation between mean shear bond strength and ARI score was found to be significant for pooled data from all groups. Significant correlation was found in Group 4 (Clarity© series brackets bonded with SEP).

Multiple chi squared (χ^2) analysis of ARI scores showed no significant correlation between test group and ARI score. However, examination of the raw data shows there to be a greater number of ARI score 3 in Group 3. This would suggest that a ‘sticking threshold’ exists when bond strength exceeds 12.4MPa (mean bond strength Group 6), resulting in more adhesive remaining on the tooth surface.

Conclusions

- Separate etch and primer provides a significantly greater bond strength than self-etch primer
- Greater amounts of adhesive remain on the tooth surface following debond when bond strength exceeds 12.4 MPa

Clinical recommendation

- Adequate bond strengths are obtained when Clarity© series brackets are bonded clinically with self-etch primer.

Acknowledgements

I dedicate this thesis to my husband and our beautiful daughter, Charlotte.

I would also like to express my heartfelt thanks to my supervisor, Dr. Rock, whose guidance has ensured the successful completion of this research.

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1.1 Introduction

1.1 Introduction

Since Buonocore (1955) introduced the acid-etch technique to dentistry, there has been discussion amongst the profession regarding the potential damage to enamel by this procedure. Zachrisson (1977) introduced bonding of orthodontic attachments to enamel surfaces following acid etching and considered bond failures and damage to the tooth surface caused by bonding and debonding. Most commonly stainless steel brackets have been used but, in response to demands by patients for better aesthetics during treatment, plastic and ceramic brackets have been introduced over the last 30 years (Russell, 2005).

Buonocore (1955) used 85% ortho-phosphoric acid for 30 seconds and reported that the bond strength of acrylic restorations was significantly increased by etching of the enamel surface. Bond strength improvement is derived by dissolution of the surface hydroxyapatite crystals to create micro-porosities into which fluid adhesive can flow (Retief, 1978).

1.2 Enamel structure, composition and characteristics

1.2.1 Enamel formation

Amelogenesis, or enamel formation, is a two-stage process. The first step produces a partially mineralized (approximately 30%) enamel. Once the full width of this enamel has been deposited, a second stage involves significant influx of additional material and water to attain greater than 96% mineral content. This mineral influx makes the crystals form, and during the first step grow wider and thicker. This complicated process is under cellular control, and the associated cells undergo significant morphological changes throughout amelogenesis, reflecting their evolving physiological activity.

1.2.2 Enamel structure

The fundamental organizational units of mammalian enamel are rods (prisms) and inter-rod enamel (inter-prismatic substance). Enamel is built from closely packed and long, ribbon-like carbonatoapatite crystals measuring 60 -70nm in width and 25-30nm in thickness. The calcium phosphate unit cell has a hexagonal symmetry and stacks up to impart a hexagonal outline to the crystal. However fully mature enamel crystal are no longer perfectly hexagonal but rather exhibit an irregular outline because they press against each other during the final part of their growth.

The rod is cylinder shaped and is made up of crystals with long axes that run, for the most part, parallel to the longitudinal axis of the rod. The inter-rod region surrounds each rod and its crystals are orientated in a direction different from those making up the rod. The boundary between rod and inter-rod enamel in this region is delimited by a narrow space containing organic material known as the rod sheath. The basic organizational pattern of mammalian enamel is described as cylindrical rods embedded in the inter-rod enamel.

1.2.3 Enamel composition and morphology

Fully formed enamel is a highly mineralized extracellular matrix, consisting of 96% mineral and 4% organic matrix and water. The inorganic content of enamel is mainly crystalline calcium phosphate, called hydroxyapatite.

The high mineral content of enamel makes it extremely hard, enabling it to withstand occlusal forces applied during function. Although the hardness is comparable to that of mild steel, enamel is brittle and the underlying layer of more resilient dentine is necessary to maintain its integrity.

Enamel is translucent and varies in colour from light yellow to grey-white. It varies in thickness from a maximum of approximately 2.5mm over working surfaces to a feather-edge at the cervical margin. This variation influences the colour of enamel as the underlying yellow dentine shines through the thinner regions.

The enamel surface is characterized by a number of distinct structures. The striae of Retzius often extend from the dentin-enamel junction to the outer surface of enamel, where they end in shallow furrows known as perikymata, which run in circumferentially horizontal lines across the face of the crown. Lamellae or cracks in the enamel appear as jagged lines. In unerupted teeth the enamel surface consists of a structureless surface layer that is lost rapidly by abrasion, attrition and erosion in erupted teeth. The striae of Retzius appear as a series of dark lines extending from the dentino-enamel junction toward the tooth surface, when viewed in transverse section.

1.3 Preparation of the tooth surface for clinical procedures

1.3.1 Prophylaxis

In vitro the tooth surface is covered by a pellicle consisting of a protein film that forms on the surface enamel by selective binding of glycoproteins from saliva. It is advisable to clean the tooth surface prior to chemical etching in order to allow ease of access of chemical etchant to the enamel surface.

The most commonly used methods of cleaning are a brush or rubber cup, used in a slow-speed handpiece, accompanied by an abrasive agent. Ideally a prophylaxis paste should be sufficiently abrasive to remove all types of accumulations from the enamel surface without causing abrasion. The most common abrasives are pumice, silica, and zirconium silicate, all of which are harder than enamel (Idatz *et al.*, 1976). It is to be expected that there will be some enamel loss when these materials are used. It has been reported that initial prophylaxis with a bristle brush for 10 to 15 seconds can abrade as much as 10μm from the enamel, whereas only 5μm might be lost when a rubber cup is used (Pus and Way, 1980; Thompson and Way, 1981).

1.3.2 Acid etch technique

Buonocore’s work on acid etching of enamel surfaces originated from industry, where phosphoric acid preparations were used to obtain better adhesion of paint and resin coatings to treated metal surfaces (Buonocore, 1955). He found that enamel treatment with phosphoric acid increased the retention of acrylic filling materials. Based on investigations by Silverstone (1974) and Retief (1974), acid solutions in concentrations of 20-50% applied for 1-2 minutes were found to produce the most retentive conditions, and they were recommended for clinical use. Gwinnett and Matsui (1967) first reported upon the ability of dental adhesive resins to penetrate subsurface microporosities created in etched ground enamel. Buonocore (1968) suggested the concept of micro-mechanical retention, identifying that resin tag formation caused the principal adhesion of resins to acid etched enamel. The clinical technique of bonding to enamel did not become established until the early 1970s since up to that time restorative materials were unsuitable.

Etching enamel with phosphoric acid changes the surface of the enamel in two distinct ways:

- Etching dissolves a shallow layer of enamel
- Etching renders the enamel porous by partially dissolving the ends of the enamel prisms.

Buonocore (1955) suggested etching the tooth surfaces using 85% phosphoric acid (H_3PO_4) for 30 seconds. Gwinnett (1971) etched enamel with 50% phosphoric acid for 2 minutes and estimated the loss of enamel tissue to be between 5 and 25μm in depth. After 90 seconds of etching with 30% phosphoric acid Fitzpatrick and Way (1977) found an average enamel loss of 9.9μm. Pus and Way (1980) treated 50 human premolars with 43% phosphoric acid gel and another group of 50 with 37% liquid ortho-phosphoric acid, all for 90 seconds. The average losses of enamel tissue were 7.5 and 6.5μm respectively. Wickwire and Rentz (1973) submitted premolars to varying etch times and concluded that enamel dissolution increased with time.

1.3.3 Etchant concentration

Soetopo *et al.* (1978) measured tensile bond strengths after etching with different 2-60% phosphoric acid solutions. 16% acid produced the highest bond strength, but the values for 2% acid were similar to those for 40%. Zidan and Hill (1986) also found no statistical difference in tensile bond strength after 1 minute application of 2%, 5% and 35% phosphoric acid whilst the loss of enamel was considerably higher with 35% acid than with 2% acid. Moin and Dogon (1974) reported the most consistently uniform and suitable etching pattern after application of 30 to 40% phosphoric acid. Rock (1974) reported significantly higher bond strengths for teeth treated with 30% phosphoric acid than with 50% phosphoric acid. 37% phosphoric acid is most commonly used clinically as it provides similar bond strengths to higher concentrations, with less damage occurring to the enamel surface (Denys and Retief, 1982; Sadowsky *et al.*, 1990; Carstensen, 1992).

1.3.4 Duration of etching

The effects of varying etch time on bond strength is still controversial, especially with respect to ceramic brackets. Britton *et al.* (1990) reported increased bond strengths after reduced etch time when premolars were etched *in vitro* for 15 and 60 seconds using 37% phosphoric acid. Gorelick (1977), evaluated the effects of 60 and 90 second etching time intervals, Barkmeier *et al.* (1985) used 15 and 60 second etching, whereas Beech and Jalaly (1980) evaluated 5, 15, 60 and 120 second intervals. All reported no decrease in bond strength as a result of shortened etch times. Osorio *et al.* (1999) reported higher shear bond strength when enamel was etched for 60 seconds and the amount of adhesive remaining on the tooth was also greater. However a 15 second etch still produced a bond stronger than that required for successful orthodontic bonding. A 15 second etch time produced a “cleaner” etch site after debond.

Bin Abdullah and Rock (1996) examined shear bond strength following 15, 30 and 60 second etch times, using 37% phosphoric acid. Debond was performed at 5 minutes, 15 minutes or 24 hours. The 15 second etch / 5 minute debond time specimens had much lower shear bond strengths than other groups. After sixty seconds of etch teeth showed evidence of tooth surface damage after debonding. The results were in accordance with work published by Bryant *et al.* (1985), Barkmeier *et al.* (1985), Wang and Lu (1991) and Sheen *et al.* (1993).

Carstensen (1986) studied the clinical failure rate of mesh-based metal brackets on 1134 anterior teeth, after etching for 30-35 seconds with 37% phosphoric acid. Only 10 brackets were lost during the 16 month study period. In a second study a comparison was made between the effects of etching for 15-20 and 30-35 seconds. The conclusion was made that 15 second etch was sufficient for bracket bonding on anterior teeth.

From this work and that of Osario *et al.* (1999), fifteen seconds of etching became routinely recommended for bonding orthodontic brackets. However if a bracket is to be ligated within 5 minutes, 30 seconds etching is recommended. A 60-second etch is considered too severe and should not be used.

1.3.5 Etch pattern

Most bond strength testing has been performed on extracted pre-molar teeth. Hobson *et al.* (1999) examined variations in shear bond strength between different tooth types. Significant differences were found for shear bond strengths between different tooth types and opposing dental arches. Upper anterior teeth gave higher shear bond strengths than upper posterior teeth and lower posterior teeth exhibited higher bond strengths than lower anterior teeth. Other evidence has suggested that different tooth types exhibit biological variations in etch patterns after acid priming (Hobson and Mattick, 1997; Hobson and Mattick, 1998) and this may influence bond strengths. Marshall *et al.* (1974) examined etched surfaces under the scanning electron microscope and reported a high degree of variation in etching pattern from tooth to tooth and in different parts of the same tooth, following the same etching procedure. Certain portions of enamel appeared to have a thicker, denser or more tightly adhering prismless layer that impeded dissolution of the underlying enamel prisms and this was more evident on premolars than molars. This led authors to postulate that molars required a longer etch time than premolars. Linklater and Gordon (2001) examined the presence and pattern of differences in ex vivo shear bond strengths between tooth types when bonding orthodontic brackets. Significant differences in mean shear bond strengths were found, with canine and pre-molar teeth exhibiting higher strengths than incisors.

1.4 Adhesion and Adhesives

1.4.1 Resin based composites (RBCs)

Composite materials consist of two or more components. A resin based composite typically contains organic binder and an inorganic filler, the particles of which are normally coated with a coupling agent to bond them to the resin matrix (Phillips, 1982).

The aromatic dimethacrylate monomer bis-glycidyl methacrylate (bis-GMA) or Bowen’s resin is often used (Bowen, 1965). Bowen’s resin, like methyl-methacrylate, undergoes free-radical addition polymerization. Its larger molecular structure with side chains capable of undergoing cross-linking means that it has a lower polymerization shrinkage and coefficient of thermal expansion than methyl-methacrylate-based adhesives. However, the larger molecular structure also means that it is very viscous and in order to make it clinically usable it is diluted with lower viscosity dimethacrylate monomers, such as diethylene glycol dimethacrylate (DEGDMA) or triethylene glycol methacrylate (TEGDMA). In recent years other dimethacrylate monomers, such as urethane dimethacrylate (UDMA), have been used to substitute for all or some of the bis-GMA. The least favourable characteristic of RBCs is volumetric shrinkage during the conversion of monomer to polymer (Combe and Burke, 2000). The resin matrix of all RBCs shrinks by approximately 10% and this causes stresses at the bonded interface with the adjacent tooth surface (Glen, 1982).

Another constituent of RBCs is a diluent monomer which reduces viscosity, enabling proper blending with the inorganic constituents to aid manipulation. The greater the concentration of diluent monomer in the formulation the lower the viscosity and the larger the effect on polymerisation shrinkage. Some manufacturers prefer a combination of UDMA and bisphenol-A-polyethylene glycol di-ether dimethacrylate (bis-EMA). This produces a less viscous mixture than bis-GMA and so obviates the need to use diluent resins and thus reduces the amount of shrinkage that would otherwise occur (Combe and Burke, 2000).

The inorganic filler particles consist of glass beads or rods, aluminium silicate, barium, strontium and borosilicate glasses. Fillers reduce the polymerization shrinkage and coefficient of thermal expansion of the material as well as improving abrasion resistance. The first RBCs had pure silica particles averaging 20μm in diameter. This size of particle limits the finish because relatively large particles are readily lost, producing a rough surface with poor lustre. Wear resistance is poor and the surface is susceptible to staining. Smaller filler particles increase the surface area of the filler and enhance polishability. Inclusion of aluminium and lithium or crystalline quartz has improved the properties of the material. Whether these factors are important in the thin section found beneath orthodontic brackets is unclear. However, properties such as Young’s modulus, tensile and compressive strengths, and wear resistance are all increased when the filler particles are able to bond to the resin matrix (Söderholm, 1985).

Resin based composites can be classified according to particle filler size:

Macro-filled	10 - 100μm
Mid-sized	1 - 10μm
Mini-filled	0.1 - 1μm
Micro-filler	<0.1μm

Modern RBCs are mini-filled, with particles averaging 0.1 – 1μm. Fumed colloidal silica filler particles of size 0.04μm are incorporated to produce a hybrid RBC with improved handling characteristics (Albers, 1996). Fumed silica increases the percentage of filler that can be introduced into the resin. A hybrid resin is a composite in which at least 7-15% of the filler is fumed silica micro-particles. A micro-filled RBC is exclusively composed of micro-filled particles. Thus the total surface area of filler is maximised but heavy loads cannot be resisted (Fortin and Vargas, 2000).

RBC may be either chemically cured, light cured or dual cured. Chemically activated RBCs use benzoyl peroxide, tertiary amine or sulphinic acid initiators have. Visible light cure composites contain an alpha-diketone such as camphorquinone and an amine. On application of visible light of wavelength 460-485nm free radicals are generated (Combe and Burke, 2000).

RBCs are not used without risk since they may cause hypersensitivity reactions to ancillary staff and clinicians. Olea *et al.* (1996) have described oestrogenic effects of bisphenol-A and Eliades *et al.* (2000) further raised concern over free-monomer containing oestrogen derivatives which may leach from a composite.

1.4.2 Glass ionomer cements (GIC)

The first glass ionomer cements contained an ion-leachable glass which reacted with a water-soluble polymer acid to yield a cement (Wilson and Kent,1971; Wilson and Kent,1972). The glass powder was formulated from a calcium aluminosilicate glass containing fluoride, whilst the set cement comprises a higher molecular weight organic-inorganic complex. A typical glass has from 6 components, fused together at 1000-1300˚c. The ratio of Al_2O_3 to SiO_2 is critical for correct reactivity. Fluoride is an important component of a GIC as it contributes to the therapeutic value of the cement, assists in the manufacture of the glass by lowering fusion temperature and enhances the working characteristics and mechanical properties of the cement (Wilson and Nicholson, 1993). Under certain conditions the fluoride content gives a more translucent glass. The sources of fluoride ions in GIC are: calcium fluoride (CaF_2), strontium fluoride (SrF_2), lanthanum fluoride (LaF_2), sodium hexa-fluoroaluminat (Na_3AlF_6) and aluminium trifluoride (AlF_3). Radio-opaque glasses are used in some materials: in these calcium may be replaced by barium or strontium.

Type I GICs are luting cements, employed in orthodontic bonding. They are fine-grain materials with low thickness when set. Most commonly they are used for cementing bands but they have also been used to bond orthodontic brackets. Type II GICs are restorative materials and Type III are lining materials and fissure sealants.

GICs sets on mixing the basic glass with an aqueous poly(alkenoic) acid to produce an acid-base reaction. The setting reaction releases hydrogen ions which penetrate the fluro-aluminosilicate glass surface and release calcium, strontium and aluminium. The final setting reaction may take weeks or months (Williams *et al.*, 1989; Williams *et al.*, 1991). Compressive strength values have been shown to increase over a year (Suzuki *et al.*, 1995) and bond strength increases for a month after which the rate slows (Choo *et al.*, 2001).

During setting the material is susceptible to hygroscopic influences. Too little water causes dehydration and an excess antagonises the setting reaction and damages the surface of the cement. Wilson and McLean (1988) reported potential problems with bond strength testing by placing newly mixed conventional GIC in water for 24 hours prior to experimentation, causing elution of ions required theoretically for the formation of the cross linked polyacrylate chains.

Glass ionomer cements adhere directly to enamel without the need for additional bonding agents and surface treatments. The primary mechanism for adhesion is derived from the ability of the acid to clean, penetrate and roughen the tooth surface which decreases surface energy and facilitates both micromechanical and chemical bonding. The carboxyl group in the polymer acid forms ionic bonds with metal ions (McClean, 1996).

Exposure of set GIC to neutral aqueous solutions leads to absorption of water and release of ions such as sodium, silica, calcium and fluoride. Fluoride present in the matrix is available for elution under neutral conditions, although this equates to a very small percentage of fluoride ions in the total set cement (Wilson and Groffman, 1985). The mechanisms of release are either short or long term. The short term reaction releases relatively high levels of fluoride during the post-setting maturation process. The long term releases of fluoride is low, due to the equilibrium diffusion gradient between the material and the environment which may cause fluoride to be absorbed or released (Forsten, 1991).

Demineralisation is apparent on at least one labial tooth surface in 50-75% of all orthodontic patients at debond (Gorelick *et al.*, 1982). The presence of demineralisation has been reported as a significant clinical problem 5 years after active orthodontic treatment (Øgaard, 1989). Fluoride release from GICs contributes to a reduction in demineralisation and also slows caries progression, although caries protection is only partial (Fricker and McLachlan, 1987; Maijer and Smith, 1988; Rezk-Lega *et al.*, 1991; Marcusson *et al.*, 1997; Ortendahl *et al.*, 1997). The anti-microbial effect of fluoride has also been demonstrated (McComb and Erikson, 1987; Scherer *et al.*, 1989; DeSchepper, 1989). However, Miller *et al.* (1999) showed no difference in decalcification rates between patients undergoing fixed appliance treatment with appliances that were bonded with either glass-ionomer or composite adhesive.

1.4.3 Resin-modified glass ionomer cements

Glass ionomer cements have been modified to mix with water-soluble resin monomers and aqueous polyacrylic acid. Termed resin modified glass ionomer cements (RMGICs), they are defined as materials that undergo both a polymerisation reaction involving the resin monomer and a significant acid-base reaction, large enough to promote a setting reaction in the dark (McClean *et al.*, 1994).

An acid-base reaction is initiated when powder and liquid are mixed as for any conventional glass ionomer cement. The reaction proceeds relatively slowly and produces a low pH (1.5). Cross-linking is initiated by an oxidation-reduction reaction or by free radicals liberated by a photo-polymerisation catalyst. A hardened mixture forms within which the acid-base reaction continues. The advantage of RMGIC is that the photo-polymeriser promotes more rapid setting and reduces the sensitivity of the material to water. The chemical reaction continues after the initiated light reaction is complete. Another advantage of RMGICs over conventional GICs is the comparative rapidity in the development of mechanical strength. The hydrogel phase usually observed with the conventional cements is not expressed after light curing because the polymerisation reaction of the monomer lends the material considerable strength.

1.4.4 Self etch primer

Self-etching primers (SEPs) evolved from the chemistry underlying dentine bonding. McClean and Kramer (1952) reported that methacrylic acid would bond to dentine. Buonocore (1955) demonstrated that glycerophosphoric acid di-methacrylate containing resin would bond to acid-etched dentine.

Polyacrylic acids have been used as alternatives to phosphoric acid in an attempt to minimize the potential damage caused by demineralization of the most superficial layer of enamel after etching with phosphoric acid. However resultant bond strengths were low (Triolo *et al.*, 1993; Olsen *et al.*, 1997; Smith, 1990).

Some new bonding systems combine a conditioning and priming agent into a single primer solution for simultaneous use on both enamel and dentine (Chigira *et al.*, 1989; Nishida *et al.*, 1993). The combination of conditioning and priming into a single treatment step, results in improvement in cost-effectiveness.

The active ingredient of a self-etching primer (SEP) is a methacrylated phosphoric acid ester. The phosphate group on the methacrylated phosphoric acid ester dissolves calcium and removes it from the hydroxyapatite lattice. Rather than being rinsed away the calcium then forms a complex with the phosphate group and is incorporated into the network when the primer polymerizes. Etching and monomer penetration of the exposed enamel rods are simultaneous.

Transbond Plus© 3M Unitek is an acidic primer used for orthodontic bonding (Brosniham and Safranek, 2000). The manufacturers claim this combined etch-primer system can reduce the time required for the bond up of fixed appliances and White (2001) estimated the overall time saved during bond up to be 65%. However calculations of time saved are dubious as pumicing and priming stages are omitted and SEPs must be agitated on the tooth surface for between 3 and 20 seconds. The manufacturers also claim the product works effectively in a moist environment. Thus isolation of the enamel surface to prevent salivary contamination may not be critical when using SEP. Cacciafesta *et al.* (2003) described the use of SEP as being less technique sensitive since the material tolerated moisture contamination. Dorminey *et al.* (2003) questioned this reported reduction in technique sensitivity and highlighted the importance of the air drying phase when using SEPs. The test group which did not use air drying after applying SEP had a significantly lower shear bond strength than the other two test groups, SEP with air drying and conventional two-stage adhesive system.

The use of SEP relies heavily on effective cleaning of the enamel surface with pumice prophylaxis prior to bonding (Ireland *et al.*, 2003; House, 2005). This stage can be omitted in conventional bonding.

There are conflicting reports of the clinical performance of SEPs and conventional etch and bond techniques. Asgari *et al.* (2002) and Aljibouri *et al.* (2004) both report good clinical performance with self-etch primer, if not better than with conventional etch and bond than two-stage etch and prime.

If the bond-failure rate using a one-stage system is similar or better than conventional two-stage systems and clinical bond up time is reduced it would be advantageous to use a one-stage adhesive system in everyday orthodontic practice. Manning *et al.* (2005) performed a prospective clinical trial assessing bond failure rates of brackets bonded with a SEP (Transbond Plus©) and a conventional acid-etched technique with control adhesive (Transbond XP©). No statistical difference was found between clinical bond failure rates for brackets bonded using SEP or a conventional acid-etch and resin technique respectively. At 6 months, the overall bond failure rate for both groups (1.8%) was low compared with other published data. The results of this study are in accordance with those of similar studies, including Aljibouri *et al.* (2003). Littlewood *et al.* (2001) for pre-coated brackets bonded using the same two-step adhesive system, reported a failure rate of 6.8% at 6 months.

Bishara *et al.* (2001) assessed the effect of a SEP on shear bond strength and compared this to conventional etch and prime *in vitro*. Use of a SEP resulted in a significantly lower but clinically acceptable shear bond strength compared to conventional etch and prime. Significantly more residual adhesive was found on tooth surfaces following SEP. Grubisa *et al.* (2004) compared the same two adhesive systems and also found that *in vitro* bond strengths were greater for the two-step adhesive than the one-step self-etching system. However both adhesives performed well clinically, suggesting that differences in in-vitro bond strengths may be clinically insignificant.

Hirani and Sherriff (2006) examined bond strengths, rebond strengths and failure sites of adhesive pre-coated brackets and conventional brackets when bonded with a SEP (Transbond Plus©) and conventional acid etching and conditioning. No difference was found in shear bond strength between APC and conventional brackets with SEP. The majority of bond failures occurred at the adhesive-enamel interface.

1.5 Orthodontic bracket design

1.5.1 Metal brackets

The first metal brackets were milled from cold drawn stainless steel and had crude perforated bases into which adhesive could flow (Sheykholeslam and Brandt, 1977). Stainless steel brackets do not form a chemical union with an adhesive but are retained at the base-adhesive interface by mechanical interlocking (Ferguson *et al.*, 1984). The original metal pads contained only one row of perforations along the outer margins and the relatively larger inner smooth surface was incapable of contributing to retention. This base design was later changed to foil-mesh bracket bases, which produced greater bond strength (Reynolds and von Fraunhofer, 1977; Lopez, 1980) and caused less plaque retention (Maijer and Smith, 1981). The foil mesh was welded to a solid metal backing. Weld points called gobbets, are un-retentive and microscopy reveals that the adhesive is prone to fracture in regions adjacent to these sites. Maijer and Smith (1981) suggested that the gobbets lead to stress concentrations in the adjacent resin, leading to lower bond strength.

Figure 1.1 3M Unitek Victory© series orthodontic bracket

1.5.2 Plastic brackets

Plastic brackets were first marketed in the early 1970s. Initially they were made from acrylic or polycarbonate and their acceptance by orthodontists as an alternative to metal brackets was short lived. Inherent problems were quickly identified, including staining and odours, but more importantly their lack of strength and stiffness resulted in bonding problems, tie wing fractures and permanent deformation (Arid and Durning, 1987). Polycarbonate bracket slots distort with time under a constant stress, rendering them insufficiently strong to withstand longer treatment times or to express torque (Dobrin *et al.*, 1975). In a simulated intra-oral situation Harzer *et al.* (2004) reported significantly higher torque losses and lower torquing moments with polycarbonate brackets than metal brackets.

To compensate for the lack of strength and rigidity of the original polycarbonate brackets, high-grade medical polyurethane brackets and polycarbonate reinforced with ceramic or fibreglass fillers and/or metal slots have been introduced. Polycarbonate brackets with metal reinforced slots demonstrate significantly less creep than conventional polycarbonate brackets although torque problems still exist.

1.5.3 Ceramic brackets

Ceramic brackets were introduced in the 1980s (Birnie, 1990). They offer advantages over steel brackets in terms of appearance. Ceramic brackets provide higher strength, more resistance to wear and deformation, better colour stability and, superior aesthetics. All currently available ceramic brackets are composed of aluminium oxide in either polycrystalline or monocrystalline form, depending on their method of fabrication. The first brackets were each milled from a single crystal of sapphire using diamond tools (Swartz, 1988). More recent monocrystalline alumina (MCA) brackets are machined from extrusions of synthetic sapphire (Swartz, 1988). Ceramic brackets are unable to bond chemically with acrylic and diacrylate bonding adhesives due to their inert aluminium oxide composition. As a result, early ceramic brackets used a silane-coupling agent to act as a chemical mediator between the ceramic bracket base and the adhesive resins. This chemical retention resulted in extremely high bond strengths that caused the enamel / adhesive interface to be stressed during debonding, risking irreversible enamel damage (Russell, 2005). The American Association of Orthodontists (1988) carried out a survey of members’ experiences with chemically-bonded ceramic brackets. The results caused the Association to advise its members regarding potential health concerns with ceramic brackets and practitioners were recommended to discuss the potential risks with their patients as part of the informed consent process (Lindquist, 1989). The majority of currently available ceramic brackets rely solely on mechanical retention, using standard light or chemically cured adhesives, without the need for additional special bonding agents.

Polycrystalline alumina brackets (PCA) are made by injection moulding of submicron-sized particles of alumina suspended in a resin, sintering them to fuse the alumina to produce a bracket that is finally machined to shape (Birnie, 1990). Polycrystalline ceramics, due to their rougher more porous surface, have a high coefficient of friction. Omana *et al.* (1992) showed that machined ceramic brackets produce significantly greater frictional forces than stainless steel brackets. Birnie (1990) discouraged the use of sliding mechanics with ceramic brackets and suggested bonding metal brackets to the premolars if this movement was required.

Property	**MCA**	**PCA**	**Stainless steel**
Hardness (Rockwell)	97.5	82.5	5-35
Tensile strength (psi x100)	260	55	30 - 40
Fracture toughness (MPa)	2 - 4.5	3 – 5	80 - 95

Table 1.1 Physical properties of alumina structures and stainless steel (Birnie, 1990)

The brittleness of ceramic brackets can cause problems at debond (Gibbs, 1992). Their hard nature can cause abrasion to the dentition and significant enamel wear has been found on the palatal surfaces of upper incisors from contact with the lower labially placed ceramic brackets after only six weeks (Douglas, 1989).

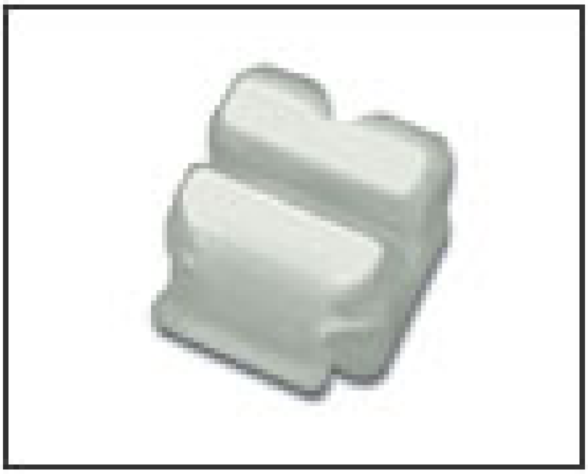


Figure 1.2 3M Unitek Transcend© ceramic orthodontic bracket

1.5.4 Metal-reinforced ceramic brackets

In an attempt to improve the frictional characteristics of polycrystalline ceramic brackets, manufacturers have introduced metal reinforced archwire slots in order to provide smoother sliding mechanics and additional strength (Clarity© brackets, 3M Unitek). Several different metal lined polycrystalline brackets are currently available with 18 carat gold inserts; these are reportedly superior to stainless steel with regard to frictional resistance (Kusy and Whitley, 2001).

Figure 1.3 3M Unitek Clarity© series orthodontic bracket

1.5.5 Bracket base morphology

The formation of the base of the orthodontic bracket has been thought to affect the mode of bond failure and to have an effect on enamel surface damage during bracket removal. Indentations or undercuts in the bracket base can provide mechanical retention. Most commonly for metal brackets, a mesh is welded to the bracket base to form a structure for mechanical retention (Matasa, 1992). Welded mesh bracket bases are not without disadvantages; clinically the pads are flexible, especially those of finer mesh size. These readily distort and bend away from the tooth surface, resulting in soft tissue trauma and unfavourably affecting the mechanical retention (Reynolds and von Fraunhofer, 1976). On debonding the components of mesh-based brackets tend to separate, leaving the wire mesh attached to the tooth (Moin and Dogon, 1978). Brazing replaced welding as the technique for attaching mesh foil to the bracket base, preventing the mesh strands from being flattened during assembly. Brackets manufactured as a separate components have a plane of weakness between the bracket and base (Dickinson and Powers, 1980).

Bond strength of foil-mesh brackets is influenced by the diameter of the wire mesh and the number and size of openings per unit area. The available free volume affects resin penetration, which is also dependent upon filler size. The influence of these variables was demonstrated by Reynolds and von Fraunhofer (1976), who found that a coarse mesh improved bond strengths. Maijer and Smith (1981) on the other hand found a fine woven mesh bracket base to result in higher values. Microscopy reveals air voids at the adhesive / base interface, possibly caused by polymerisation shrinkage or by air entrapment during bracket placement. Knox *et al.* (2000) investigated the influence of bracket base morphology and orthodontic bonding agent on adhesion strength and concluded that the adhesive had great influence upon bond strength and that particular base designs may improve adhesive penetration or improved penetration of a curing light.

The literature provides conflicting reports regarding the effect of using different retentive bracket base designs on shear bond strength. Bishara *et al.* (2004) tested shear bond strengths of two metallic brackets, one with a single-mesh bracket base and the other with a double-mesh bracket base using Transbond XT© adhesive. The shear bond strengths for both test groups were similar and the Adhesive Remnant Index (ARI) comparisons indicated that both bracket types had similar bracket failure modes. These results indicated that single and double mesh bracket bases have comparable shear bond strengths and bracket failure modes. Brackets with a single-mesh bracket base (Victory© series) have been selected for the present study.

Although ceramic brackets offer better aesthetics, concerns have been raised as to an increased risk of enamel surface damage on debonding, although Wang *et al.* (1997) found no statistical difference in bond strengths between ceramic and metal brackets. Enamel detachment was found only when there was a chemically coated base on the ceramic bracket and consequently higher bond strengths. Some ceramic brackets use a silane coupler as a chemical mediator between the bracket base and the adhesive resin (Wang *et al.*, 1997). Silane treatment of a smooth ceramic bracket base unites the silica component of the bracket with the composite resin to produce a chemical bond. Silane-treated ceramic brackets exhibit unpredictable and extremely high bond strengths, which increase the risk of tooth damage (Forsberg and Hagberg, 1992).

Manufacturers sometimes apply a textured base to ceramic brackets e.g. Transcend© 1000 (3M Unitek). Bond strength is lower than for silane treated brackets but higher than for stainless steel. It has been suggested that the microcrystalline retentive material of ceramic brackets provides opportunities for stronger interlock between bracket and adhesive than does the foil of metal brackets (Forsberg and Hagberg, 1992). Habibi *et al.* (2007) compared the debonding characteristics of metal and ceramic brackets and concluded that the risk of enamel damage when debonding mechanically – retained ceramic brackets was no greater than the risk when debonding metal brackets.

The continuing challenge is to develop a bond between orthodontic attachments and enamel that is strong enough to survive a course of treatment but can be broken for debonding without damage to the enamel surface (Bishara *et al.*, 1994). For this reason the bracket systems selected for the present investigation had similar mechanically retentive bracket bases.

1.5.6 Adhesive pre-coated brackets

Fox *et al.* (1994) stressed the importance of standardization in bond strength testing. In order to standardize the amount of composite on the bracket base the use of adhesive pre-coated brackets (APC) is to be employed in the present study. Both metal and ceramic brackets have been available since 1991 as adhesive pre-coated versions. The pre-coated composite used is a version of Transbond© XT (3M Unitek), modified to give increased viscosity. It can be used in conjunction with Transbon© Plus Self-Etching Primer (TPSEP). APC brackets were originally designed in an attempt to save chairside time by allowing faster and easier bonding procedures. Cooper *et al.* (1992) listed the following advantages of APC over conventional light-cured systems:

- Consistent quality and quantity of light-cured adhesive
- Easier clean-up following bonding
- Reduced waste
- Improved infection-control
- Better inventory control

In addition improved control of both the bracket and adhesive with the use of APC is claimed to improve bond strength and thereby reduce clinical failure rate (3M Unitek Product Literature, 1997). An advantage of light-cured adhesives is that they provide the orthodontist with ample time to position the bracket on the enamel surface accurately before polymerization. A disadvantage of the light-cured approach is the time it takes to expose each bonded bracket to the light (Sfondrini *et al.*, 2002).

Only a few studies have evaluated the bond strength of APC brackets. Bearn *et al.* (1995) compared the *ex-vivo* shear bond strength of metallic APC brackets with that of identical brackets bonded with Transbond© XT and found no statistical differences between the two. Sfondrini et al (2002) reported significantly higher bond strengths with non-APC brackets, cured with a halogen light curing unit, a finding supported by the results of similar work (Bishara *et al.*, 1997; Sunna and Rock, 1999; Ash and Hay, 1996). A possible explanation suggested by Bishara *et al.* (1997), was that the increased viscosity of the adhesive used on the APC brackets, when combined with the mesh retention incorporated in the metal bracket base, may significantly reduce shear bond strength. In response to this data, the manufacturer modified the adhesive used for pre-coating (APC1 to APC2).

It appears that the duration and intensity of light exposure is critical to the shear bond strength of APC brackets. Bearn *et al.* (1995) used a longer light-curing time (30 s) than suggested by the manufacturer. Sunna and Rock (1999) found that APC brackets cured for 40 seconds with a halogen unit had similar bond strengths to uncoated brackets bonded with Transbond© XT. This is in agreement with Wang and Meng (1992), who reported higher bond strengths with Transbond© XT when light-curing was increased from 20 to 40s. Ip and Rock (2004) reported that the use of a plasma light conferred worthwhile time savings when bonding orthodontic brackets, whilst producing bonds of equivalent strength to those found with quartz halogen lights.

Reynolds (1975) suggested a clinically acceptable shear bond strength to be in the order of 6-8MPa. Sfondrini *et al.* (2002) reported bond strengths greater than this regardless of the light or bracket type used. Even light-curing for 2 s with the micro-xenon light produced clinically acceptable bond strengths of both uncoated and pre-coated brackets. The reduced curing time achieved by means of the micro-xenon light represents a great advantage for both the patient and the clinician.

1.6 Bracket removal

1.6.1 Bond strength testing

The literature contains a large number of publications on *in vitro* bond strength testing of materials, the results of which are quoted by manufacturers in support of their products. However little attention has been paid to the detail of the test procedures used. Fox and McCabe (1994) published a critique of bond strength testing in orthodontics, which revealed a large variation in the methods used, and the case for a possible standard technique was suggested. Van Noort *et al.* (1989) and Rueggeberg (1991) both suggested the need for standardization of test procedures for the measurement of bond strengths, to allow valid comparisons to be made between different bonding agents.

Hobson and McCabe (2002) investigated the relationship between enamel etch characteristics and resin-enamel bond strength. 28 patients had the buccal surfaces of teeth etched and replicated for examination under the scanning electron microscope. No statistical difference was found in etch patterns between upper and lower teeth. However mean bond strength varied significantly between different tooth types, with the lowest bond strength found on the upper first molar and the highest on the lower first molar. An ideal etch pattern was not essential in order to produce a strong bond.

Shear bond strength with SEP has been compared with conventional two-stage bonding systems in laboratory studies. Brackets bonded with the SEP were found to have a significantly lower mean shear bond strength compared with those bonded with a conventional two-stage adhesive system (Bishara *et al.*, 2001; Aljubouri *et al.*, 2003). However following the application of mechanical stress, the mean survival times for brackets bonded with either the SEP or the conventional two-stage bonding systems were similar (Aljibouri *et al.*, 2003).

1.6.2 Unit of measurement of bond strength

There has been confusion in the literature over the unit of measurement most appropriate for describing bond strength (Fox and McCabe, 1994). Units such as Pascals, MegaPascals, Newtons per millimeter squared or MegaNewtons per metre squared have been used. These units provide an indication of the force per unit area required to dislodge the bracket. The use of force as an indicator of bond strength is only appropriate where the area is well controlled, but difficult to measure. As long as the dimensions of the bracket base are quoted, the use of Newtons or MegaPascals is appropriate in quoting bond strength.

1.6.3 Direction and method of debond

In 58 out of 66 papers examined by Fox and McCabe (1994), an Instron or similar testing machine was used. Other devices used included a pair of specially designed opening pliers (Perry, 1980) and various other testing machines (O'Brien *et al.*, 1991; Newman, 1965; Hirce, 1980). Forty four of the papers examined tested the specimens in shear mode, 16 in tensile and six used a combination of directions.

Further examination of the papers that reported using an Instron testing machine reveals further differences in the method and direction of debond. A problem arises with the precise relationship of the bracket and its link with the testing machine. The majority of studies use a wire loop around the bracket to connect it to the machine, as in Figure 1, where three possible directions of a debonding force vector are indicated.

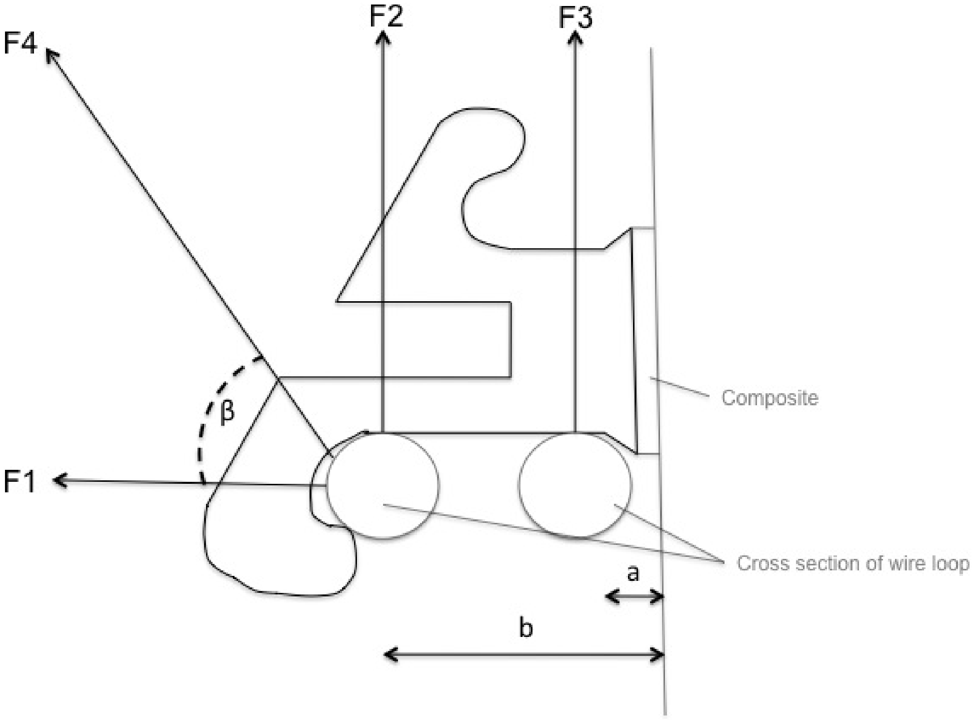


Figure 1.4 Diagrammatic representation of the relationship of the displacing wire loop to the bracket and bonding agent.

F1 = force vector used for a tensile test

F2 and F3 = force vectors used for a shear test

F4 = actual force vector, at an angle β away from the long axis of the bracket

a and b = varying distances that a shear force is away from the bracket / composite interface

Assuming that the thickness of the bonding composite and the nature of the enamel surface is identical in each case, if the forces F1, F2 or F3 are able to dislodge the bracket they would probably have different values. F1 produces a tensile stress, whilst force vectors F2 and F3 produce shear stresses. A further problem is that neither vectors F2 or F3 are testing the true shear strength of the system. In order to achieve this, the debonding force would have to be applied directly to the junction of the bracket and the composite. Vector F2 is further away from the interface thus producing more of a peel element to the debonding force, which will affect the magnitude of the force required to dislodge the bracket. It is most likely that the majority of the testing performed has been done using force vector F4. In order to minimize these differences it is suggested that if a loop is to be used to apply the debonding force it should fill the entire bracket slot so that the application is at the same distance from the bracket/resin interface in all cases. In addition, the specimen should be mounted on a universal joint to eliminate variation in the direction of the debonding force.

The majority of research into shear bond strength with a universal testing machine has applied unilateral forces to the test specimen. The results cannot be applied to clinical debonding (Fernandez and Canut, 1999; Olsen *et al.*, 1996; Olsen *et al.*, 1997). Debonding with sharp-edged pliers that apply a bilateral force at the bracket base-adhesive interface has been found to be an effective method of debonding ceramic brackets (Farquar, 1986), and its use *in vitro* simulates more closely the debonding forces applied in actual clinical situations (Bishara *et al.*, 1994; Bishara *et al.*, 1995; Bishara *et al.*, 1993).

1.7 *In vitro* assessment of enamel surfaces

Studies assessing tooth surface conditions following debonding have used linear contact measuring devices. Quantitative measurements were made for visualising enamel surfaces before and after debonding with a miniaturized Boley gauge (Brown and Way, 1978), or by optical profilometric techniques. Both techniques allowed only a few measurements per tooth surface and thus may have created less accurate final results. Digital scanning and associated software has improved the accuracy of assessment. Quick *et al.* (1992) developed a scanning ruby laser digitizer to scan and measure dental impressions and casts. The accuracy of this system needs to be enough to measure differences of up to 40μm. Van Waes *et al.* (1997) assessed loss of enamel caused by orthodontic bracket bonding and debonding using a mechanical computerized 3D scanner with resolution of 1μm.

Al Shamsi *et al.* (2007) describe the use of a fast, non-contacting laser probe which scans 8000 to 14,000 measured points per second, depending on surface topography, allowing enhanced visualisation of the enamel surface. The accuracy of the laser was found to be up to 8μm with reproducibility of 2μm. The reported values were in line with those of Mehl *et al.* (1997).

Lee and Lim (2008) reported on the use of a 3D laser profilometer to measure the amount of residual adhesive following removal of orthodontic brackets cemented using three different adhesives. The use of the Adhesive Remnant

Index (ARI) has provided rank scores, but not a true numerical value. It is also a surface area assessment, and not 3-dimensional volumetric measure.

Chapter 2

Materials and Methods

Chapter 2 – Materials and Methods

2 Materials and Methods

Laboratory testing was divided into two distinct phases:

1. Measurement of shear bond strength of three orthodontic brackets when bonded with the same adhesive and differing tooth surface preparation methods. Shear bond strength was measured using an Instron universal testing machine

2. Assessment of remaining adhesive and enamel surface damage of each tooth sample following bracket removal, according to the Adhesive Remnant Index (ARI).

2.1 Tooth specimens

Test specimens were prepared from maxillary and mandibular premolar teeth, previously extracted for orthodontic purposes. These teeth are extracted relatively frequently, making them easy to obtain. The teeth had been extracted from patients attending Birmingham Dental Hospital. This lies in an artificially fluoridated area, with one part per million of fluoride ion in the water. It is likely that all or the vast majority of the extracted teeth were taken from patients living within this area.

The Human Tissue Act (2004) provides a legislative framework for matters relating to body donation and the removal, use and storage of human organs and tissue. The storage and use of extracted teeth for research comes under these guidelines. In accordance with the Human Tissue Authority (HTA) guidelines, consent is not required from donors when anonymised tissue is used for research. This research was registered with and approved by the University of Birmingham Research and Ethics Committee.

Following extraction, the teeth were stored in specimen tubes containing distilled water and thymol crystals (0.1% weight / volume) to inhibit bacterial growth (Silverstone, 1967). Specimens were subsequently stored in the dark at 10° +/- 5° (Fox *et al*., 1994). Time lapse from extraction to testing ranged up to 12 months.

Inclusion criteria for tooth specimens were as follows:

- Intact labial enamel surface
- Specimen correctly stored following extraction

Exclusion criteria were:

- Caries
- Restorations in the tooth
- Gross enamel hypoplasia
- Enamel defects
- Cracking of labial enamel surface
- Specimen stored incorrectly following extraction

All teeth were examined under normal surgery light conditions to assess suitability for inclusion. Pronounced cracking was designated as those teeth with cracks detectable by direct visual inspection (Zachrisson *et al*., 1980).

Tubes containing the stored teeth were placed into a box and allocated in rotation to each of the six test groups by a process of physical randomization.

2.2 Tooth preparation

The root of each tooth was sectioned 1mm below the cemento-enamel junction using a motorized circular bone saw, with water coolant spray. Specimens were then stored in distilled water to prevent dehydration.

The sectioned crowns were mounted in self-curing orthodontic acrylic resin contained within brass cylinders (8mm radius, 43mm length). Wax wadding was used to partially fill the tubes, allowing a depth of 20mm of self-curing acrylic resin in which to embed the specimen teeth. The sectioned crown was embedded so the labial surface was parallel to, and projected slightly above the rim of the cylinder. Specimens were then stored at room temperature in distilled water, again to prevent dehydration of the enamel (Bin Abdullah and Rock, 1996).

2.3 Enamel surface preparation

Enamel preparation and bracket bonding was standardized in the following way:

1. Labial enamel surfaces were polished with fluoride free pumice slurry using a rubber prophylaxis cup attached to a slow handpiece for 10s.

2. Rinsed with air / water spray for 15 s and dried with a stream of oil-free compressed air for 10 s.

3. 6 test groups, each containing 30 sectioned teeth, were prepared.

2.4 Power calculation

The number of specimens required per group was calculated using data from Sunna and Rock (1999) and applying a power calculation (Altman, 1991). The mean bond strength reported by Sunna and Rock (1999) was 18 MPa, with a standard deviation of 2.4 MPa over a series of 7 sets of tests. The clinically relevant difference was set at 3 MPa to produce a standardized difference of 3 / 2.4 = 1.25. Using Altman’s nomogram this produces a recommended sample size of 28 for 80% power at $P < 0.01$.

Table 2.1 Test groups

GROUP	DESIGNATED ETCH	PRIMER	ADHESIVE	BRACKET TYPE
1	Phosphoric acid (37%)	Transbond© Plus	Transbond© XT	Victory© APC II
2	Nil	Transbond© Plus SEP	Transbond© XT	Victory© APC II
3	Phosphoric acid (37%)	Transbond© Plus	Transbond© XT	Clarity© APC II
4	Nil	Transbond© Plus SEP	Transbond© XT	Clarity© APC II
5	Phosphoric acid (37%)	Transbond© Plus	Transbond© XT	Transcend© APC II
6	Nil	Transbond© Plus SEP	Transbond© XT	Transcend© APC II

Group 1 – Phosphoric acid etch, Primer, Victory© series APC II bracket

The exposed enamel surface was etched with 37% ortho-phosphoric acid for 30 s. Etch was applied to the tooth surface with a brush and agitated during the etching period. The etched surface was then washed with water for 15 s and dried with oil-free compressed air until the surface of the etched enamel had a frosty appearance.

Transbond© XT primer (3M Unitek, Monrovia, California) was applied to the etched surface and the tooth lightly blown with a stream of oil-free compressed air to ensure that a thin layer of primer remained before light curing for 10 s.

An upper premolar Victory© series bracket pre-coated with Transbond© XT composite (APC II), was applied directly to the etched and primed tooth surface and seated with a consistent 700 g force, calibrated using a Correx force gauge. Excess adhesive was cleared from around the bracket periphery and the bonding material polymerized by exposure to light intensity of 740 mW / cm^2 and wavelength 470 – 480 nm for 20 s.

Group 2 – Self etching primer, Victory© series APC II bracket

Excess water was removed from the labial enamel surface, but the bonding surface kept moist, as per the manufacturers instructions. Transbond© Plus self-etching primer (SEP) (3M Unitec, Monrovia, California) was activated using thumb pressure against the sequenced pouches in the dispensing sheath. SEP was transferred to the prepared enamel surface using the applicator brush provided. This was rubbed into the exposed enamel surface for 15 seconds with the microbrush. The primed surface was then lightly blown with a stream of oil-free compressed air to disperse the solution into a thin film and allow evaporation of the carrier solvent, leaving a glossy enamel surface. A new sheath and applicator was used for each specimen.

An upper premolar Victory series bracket pre-coated with Transbond© XT (APC II) adhesive was applied directly to the prepared tooth surface and seated with a consistent 700 g force, measured using a Correx force gauge. Excess adhesive was cleared from around the bracket periphery and the bonding material polymerized by exposure to light intensity of 740 mW / cm^2 and wavelength 470 – 480 nm for 20 s.

Group 3 – Phosphoric acid etch, Primer and Clarity© series APC II bracket

The specimens for Group 3 were prepared as for Group 1. An upper premolar Clarity series bracket, pre-coated with Transbond© XT (APC II) was applied and bonded directly to the tooth surfaces as per Group 1.

Group 4 – SEP and Clarity© series APC II bracket

The specimens for Group 4 were prepared as for Group 2, ensuring the labial tooth surfaces were moist prior to preparation with the SEP. An upper premolar Clarity© series bracket, pre-coated with Transbond© XT (APC II) was applied and bonded directly to the tooth surfaces as per Group 2.

Group 5 – Phosphoric acid etch, Primer and Transcend© series APC II bracket

The specimens for Group 5 were prepared as for Group 1. An upper premolar Transcend© series bracket, pre-coated with Transbond© XT (APC II) was applied and bonded directly to the tooth surface as per Group 1.

Group 6 – SEP and Transcend© series APC II bracket

The specimens for Group 6 were prepared as for Group 2. An upper premolar Transcend© series bracket, pre-coated with Transcend© XT (APC II) was applied and bonded directly to the tooth surface as per Group 2.

2.5 Bracket placement

Brackets were bonded in all groups to the labial surface at the intersection of the long axis of the clinical crown (LACC) and the clinical crown long axis midpoint (LA point) (Andrews, 1976).

Each bracket was seated directly into the correct position and force applied of 700 g for 5 s, measured using a Correx force gauge. Peri-bracket excess adhesive was removed using a number 9 sharp probe and pressure reapplied for a further 5 s.

Each specimen was individually light cured in accordance with the manufacturer's instructions using an Ortholux LED curing light (3M Unitec, Monrovia, California). A standard 20 s cure time using an 8.3mm diameter curing tip at a light intensity of 740 mW/cm^2 and wavelength 470 – 480 nm was used. The frequency of the light emitted was calibrated before use with the in-built light intensity meter. The light tip is placed on the sensor and an indicator light shows whether the output is adequate. Variation in exposure times would affect the bond strength (Bishara *et al*., 1998; Wang and Meng, 1992; Oesterle *et al*., 1995).

All specimens were allowed to bench cure for 10 min before being placed in a hot water bath (Grant Instruments) filled with distilled water and maintained at 37° +/- 1°C for 24 hours in darkness. Leaving the specimens for 24 hours prior to debonding does not reflect clinical practice. However it does allow adhesive cements to mature to optimal bond strength (Chamda and Stein, 1996). The ISO document CD TR 11405 recommends specimens to be placed in water at 37° for short-term storage of 24 hours.

2.6 Bracket selection

Groups 1 and 2 were bonded with Victory© series APC II brackets (3M Unitek, Monrovia, California). This is a metal twin bracket with a pad design base, incorporating an 80 gauge woven mesh bonding surface, matching the curvature of the tooth for maximum contact and strong, consistent bond strength (3M Unitec, Monrovia, California).

Groups 3 and 4 were bonded with Clarity© series APC II brackets (3M Unitek, Monrovia, California). Clarity© series self-ligating brackets are made from a polycrystalline ceramic with a metal slot and nickel titanium clip. The bonding base is geometrically designed for optimal tooth fit with a micro-crystalline, mechanical locking bonding surface. The smooth molded features facilitate direct and indirect bonding techniques. The bracket base is designed with a

V-shaped groove running occluso - gingivally. With the recommended debonding pliers (3MUnitek, Monrovia, California), internal collapse of the bracket occurs on debonding and consequently removal from the tooth with minimal surface damage.

Groups 5 and 6 were bonded with Transcend© series APC II brackets (3M Unitek, Monrovia, California). Transcend© series are an all-ceramic conventionally ligated, twin bracket. The manufacturers recommend use of a specifically designed debonding tool to minimize enamel surface damage when removing brackets. Again the plier encourages the bracket to collapse internally and peel away from the tooth surface.

2.7 Bond strength testing

Each brass cylinder with its embedded specimen was assembled in the customized jig in the lower cross head of the Instron Universal testing machine (Model 5544, Instron Inc., Canton, Massachusetts, USA). The jig had a cylindrical hole (8 mm radius) into which each brass cylinder was fitted. The brass cylinder could be adjusted in both a rotational and in-out direction, enabling shear forces to be directed at right angles to the long axis of the bracket body. Specimens were mounted purposely to direct the applied force occluso - gingivally and parallel to the labial tooth surface.

A shear-peel force was applied through a looped stainless steel wire (0.016” x 0.016”, 5 mm wide, 68 mm long) engaged between the fixed upper crosshead and the occlusal tie-wings of the bracket. Wire of this dimension fills the entire width between the bracket base and tip of the occlusally facing tie-wing. This ensures that the point of application is at the same distance from the bracket / resin interface in all cases, helping to make the method of testing more reproducible. This distance was fixed for each specimen, an increase in distance from the tooth would increase the bond strength (Katona, 1997). During testing the Instron had a 2 KN load cell and cross-head speed of 1.0mm / min (Sunna and Rock, 1999).

Bespoke Merlin software electronically connected to the Instron machine recorded the results of the load applied at failure in Kg and Newtons and this data was subsequently converted to MPa.

$$\text{MPa} = \frac{\text{Load (mass) (Kg)}}{\text{Bracket base area}} \quad \text{X} \quad \text{gravitational acceleration constant (9.81)}$$

1 Kg = 9.81 N

1 MPa = N / mm^2

The bracket base size for each bracket type was determined by taking the average sum of the widths and lengths of 10 brackets measured using digital calipers, accurate to 0.01 mm.

It is impossible to apply a pure shear load to a bracket, due to an unavoidable inherent bending moment. The term ‘shear–peel’ is used in the literature to acknowledge this phenomenon (Katona, 1997). In vivo, varied forces are exerted onto the brackets and stress distributions generated within the adhesive are complex (combination of shear, tensile and compressive force systems). The Instron, is therefore more likely to create shear-peel forces that mimic the clinical situation although never truly represent it (Tavas and Watts, 1979).

Figure 2.1 Laboratory set-up: Instron Universal Testing Machine

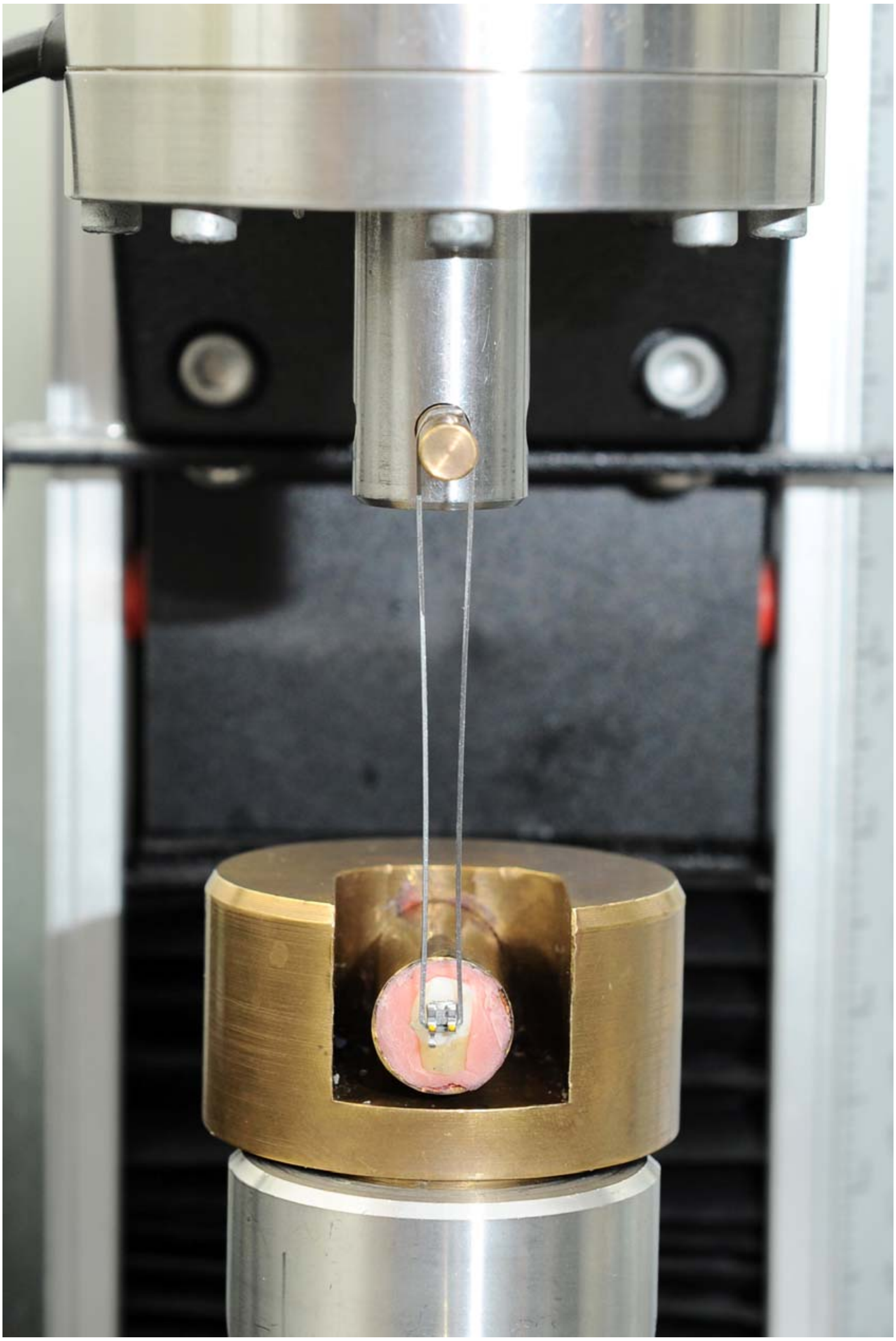


Figure 2.2 Close up view of crosshead of Instron Universal Testing Machine with sample *in situ*

2.8 Examination of enamel surface following debond

Immediately following debond, specimens were stored in de-ionised water at 10º +/- 5º C in a darkened room.

The Adhesive Remnant Index (ARI) (Årtun and Bergland, 1984) was used as a means to assess the residual adhesive and the site of bond failure (Table 2.2). Under x10 magnification the debonded enamel surfaces were examined with a stereo optical microscope and calibrated graticule. All 180 specimens were analysed in this way.

Table 2.2 ARI (Årtun and Bergland, 1984)

0	No adhesive left on the tooth
1	Less than half of the adhesive left on the tooth
2	More than half of the adhesive left on the tooth
3	All adhesive left on the tooth, with distinct impression of the bracket mesh

2.9 Method error calculation

Thirty specimens were randomly selected and scored a second time following the first analysis. The standard error of method, as calculated using Dahlberg’s formula (1940) was below the level of statistical significance, $P > 0.05$ (see Appendix 2).

2.10 Statistical analysis

The shape of each group's frequency distribution was described using box and whisker plots, which represent median, range extremities and distance between quartiles. Mean and standard deviations were also calculated.

Analysis of variance (ANOVA) was used to assess for a statistically significant difference in mean values between test groups for shear bond strength. This is appropriate in that there were greater than two independent test groups and the data is nominal. However it does assume that the data was normally distributed.

Student T-test was applied to assess the variance in mean values for groups 1 and 2, 3 and 4 and 5 and 6. This test also requires the data to be nominal and assumes the group results to be normally distributed. This was indicated as Table 3.8 shows only a small difference between groups 1 and 2 and is not clearly significantly different.

Linear correlation between shear bond strength and ARI score was measured using Pearson's correlation coefficient by individual test group and for pooled data.

Multiple chi squared testing was used to examine for significance of ARI score by group.

2.11 Materials

- 180 specimen tubes
- 180 human premolars
- Distilled water
- Thymol crystals
- Motorised circular bone saw
- Red ribbon wax
- Brass cylinders (8mm radius, 43mm length)
- Self-curing acrylic resin
- Instron jig
- 0.016 x 0.016” stainless steel loop (5mm x 68mm)
- Instron universal testing machine (Model 5544)
- Stereo optical microscope
- Calibrated graticule / eye piece (x10 magnification)
- 60 upper premolar Victory© series APC II Twin brackets
- 60 upper premolar Clarity© series APC II brackets
- 60 upper premolar Transcend© series APC II brackets
- 37% ortho-phosphoric acid
- Transbond© XT primer
- 90 Transbond© plus self-etching primer sheaths and applicators
- Correx force gauge
- Stop watch
- Water bath incubator
- Hydroflask

- Yellow soft paraffin wax BP
- Right angled probe
- Bracket holders
- 3 in 1 syringe tips
- Oil free compressed air supply

Chapter 3

Results

Chapter 3 – Results

3.1 Summary Results

Table 3.1 Summary results for each test group

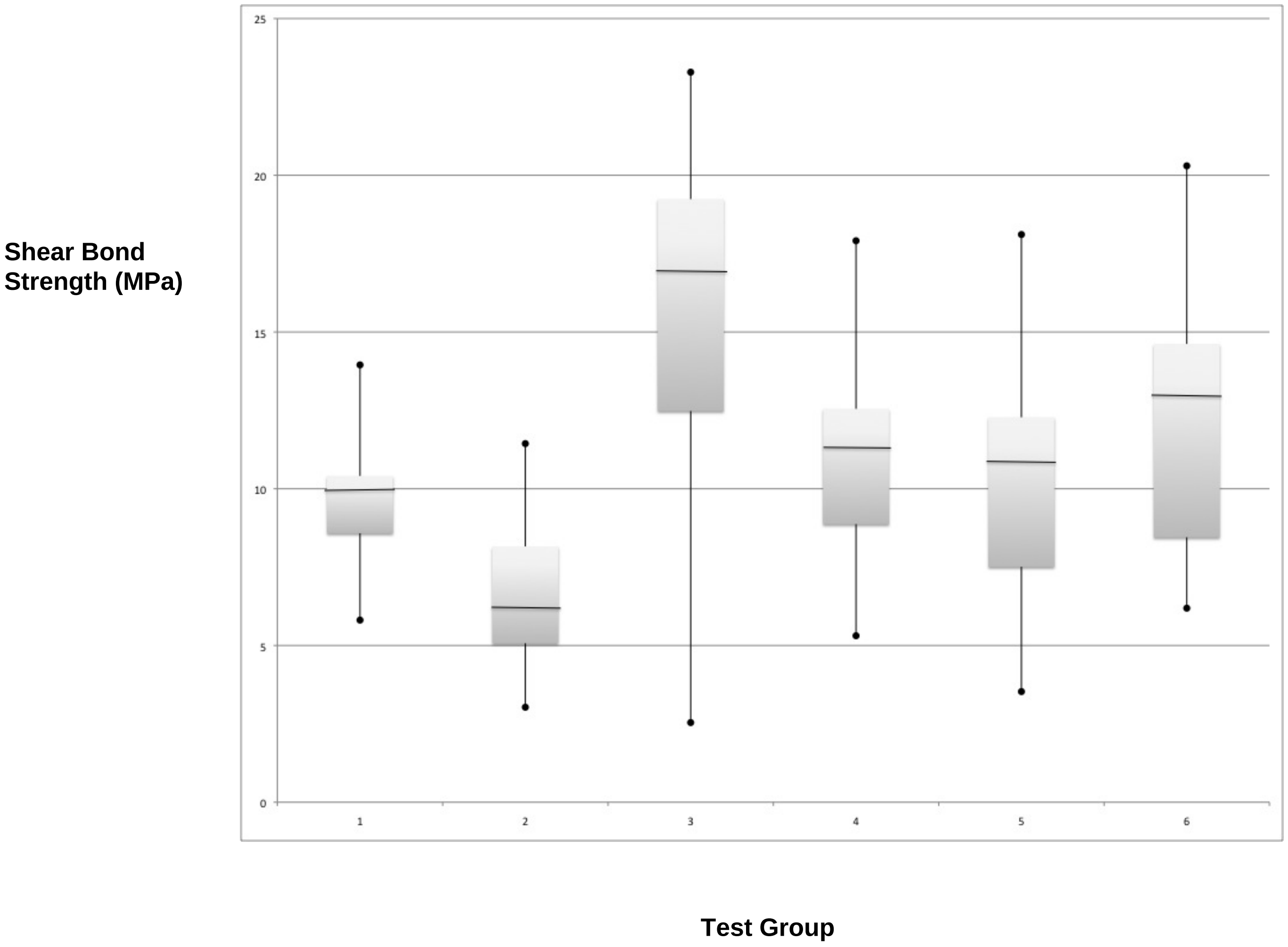
Test Group	Enamel preparation	Bracket type	Mean (MPa)	SD	Minimum	Maximum
1	Etch and prime	Victory	9.802	1.97	5.81	13.95
2	SEP	Victory	7.083	2.58	3.03	11.44
3	Etch and prime	Clarity	15.96	5.16	2.54	23.29
4	SEP	Clarity	11.27	3.45	5.31	17.91
5	Etch and prime	Transcend	10.56	3.72	3.53	18.11
6	SEP	Transcend	12.437	4.17	6.19	19.92

For raw data, see Appendix 1.

Key:

Group 1	Etch, Primer and APC Victory© brackets
Group 2	SEP and APC Victory© brackets
Group 3	Etch, Primer and APC Clarity© brackets
Group 4	SEP and APC Clarity© brackets
Group 5	Etch, Primer and APC Transcend© brackets
Group 6	SEP and APC Transcend© brackets

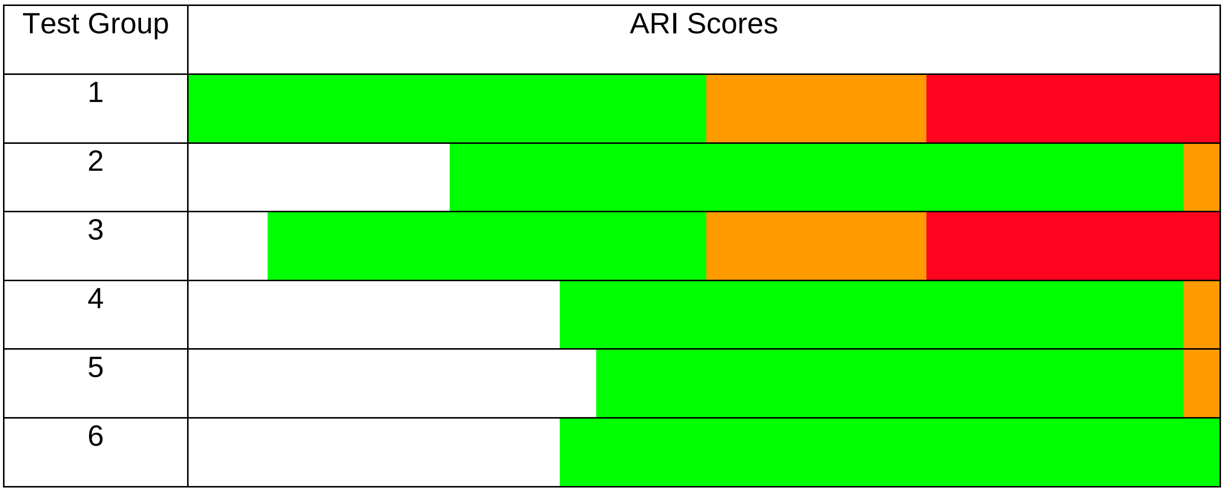
Figure 3.1 Frequency distribution of each test group represented by Box and Whisker plot (Tukey, 1977)



Key:

Group 1	Etch, Primer and APC Victory© brackets
Group 2	SEP and APC Victory© brackets
Group 3	Etch, Primer and APC Clarity© brackets
Group 4	SEP and APC Clarity© brackets
Group 5	Etch, Primer and APC Transcend© brackets
Group 6	SEP and APC Transcend© brackets

Figure 3.2 Graphical representation of ARI Score by test group



Key:

⬜ ARI score 0

🟩 ARI score 1

🟧 ARI score 2

🟥 ARI score 3

Group 1	Etch, Primer and APC Victory© brackets
Group 2	SEP and APC Victory© brackets
Group 3	Etch, Primer and APC Clarity© brackets
Group 4	SEP and APC Clarity© brackets
Group 5	Etch, Primer and APC Transcend© brackets
Group 6	SEP and APC Transcend© brackets

Mean shear bond strength varied between test groups. In ascending order, the lowest mean shear bond strength was 7.083 MPa for Group 2, Victory© brackets bonded with SEP. The second lowest mean bond strength was 9.802 MPa for Group1, Victory© brackets bonded with etch and primer. Transcend© brackets bonded with etch and primer had the third lowest mean bond strength of 10.56 MPa. Fourth lowest was Clarity© brackets bonded with SEP with a mean bond strength of 11.27 MPa. The second highest mean bond strength was 12.437 MPa for Transcend© brackets bonded with SEP and the highest mean bond strength was for Clarity© brackets bonded with etch and primer. The mean bond strength for this group was 15.96 MPa.

Standard deviations (SD) for the data varied between Groups; the largest was in Group 3, Clarity© series brackets bonded with etch and primer. The smallest SD was in Group 2, Victory© series brackets, bonded with SEP.

3.2 ANOVA for bond strengths by test group

Table 3.2 ANOVA for bond strengths by group

```
                                      Individual 95% CIs For Mean Based on
                                      Pooled SD

Group   N    Mean         SD          -+---------+---------+---------+--------

1       30   9.802        1.973            (----*---)
2       30   7.007        2.578       (---*----)
3       30   15.96        5.157                          (---*----)
4       30   11.271       3.455              (----*---)
5       30   10.562       3.722             (---*----)
6       30   12.437       4.167                 (---*----)
                                       -+---------+---------+---------+--------
                                       6.0     9.0     12.0     15.0
```

ANOVA R-Sq(adj) = 34.42%, F=19.79, P<0.01.

Key:

Group 1	Etch, Primer and APC Victory© brackets
Group 2	SEP and APC Victory© brackets
Group 3	Etch, Primer and APC Clarity© brackets
Group 4	SEP and APC Clarity© brackets
Group 5	Etch, Primer and APC Transcend© brackets
Group 6	SEP and APC Transcend© brackets

3.3.1 Two-sample T-Test for Group 1 vs. Group 2, Group 3 vs. Group 4 and Group 5 vs. Group 6

Table 3.2 Two-sample T-Test for Group 1 vs. Group 2, Group 3 vs. Group 4 and Group 5 vs. Group 6

	N	**Mean**	**SD**	**SE Mean**
Gp 1	30	9.80	1.97	0.36
Gp 2	30	7.01	2.58	0.47

T-Value = 4.72, p < 0.01

	N	**Mean**	**SD**	**SE Mean**
Gp 3	30	15.96	5.16	0.94
Gp 4	30	11.27	3.45	0.63

T-Value = 4.14, p < 0.01

	N	**Mean**	**SD**	**SE Mean**
Gp 5	30	10.562	3.722	0.679
Gp 6	30	12.437	4.167	0.761

T-Value = 1.84, p > 0.05

Key:

Group 1	Etch, primer and APC Victory© brackets
Group 2	SEP and APC Victory© brackets
Group 3	Etch, Primer and APC Clarity© brackets
Group 4	SEP and APC Clarity© brackets
Group 5	Etch, Primer and APC Transcend© brackets
Group 6	SEP and APC Transcend© brackets

Table 3.4 Two-sample T-Test for pooled etch and primer vs. pooled SEP data

	N	Mean	SD	SE Mean
Pooled etch and primer	90	12.11	4.70	0.49
Pooled SEP	90	10.24	4.15	0.44

T-value = 2.83, $p < 0.01$

ANOVA analysis demonstrated that there were statistically significant differences in shear bond strength between Groups. The mean bond strength for Clarity© series brackets bonded with etch and primer was significantly higher than that in all other test groups, whilst the mean shear bond strength for SEP and Victory© series brackets was significantly lower than the mean bond strength in all other Groups. The mean difference between Group 1 and 2 appears small but Table 3.9 shows that the results of a Two-sample T-Test indicate a significant difference in mean values between Groups 1 and 2.

The use of separate etch and primer (Group1), produced a significant increase in bond strength over the use of SEP with Victory© series brackets (Group 2) ($T= 4.72$, $p<0.01$). Similarly, separate etch and primer and Clarity© series brackets (Group 3) produced a significant increase in bond strength than with SEP and Clarity© series brackets (Group 4) ($T = 4.14$, $p<0.01$). However the two etching regimes had no significant effect on the bond strength for Transcend© brackets ($T = 1.84$, $p>0.05$).

Pooling results for separate etch and primer and SEP demonstrated a significant difference in mean bond strength between the two methods. Separate etch and primer produced significantly greater mean bond strength than SEP ($T = 2.83$, $p < 0.01$).

3.3 Correlation analysis for bond strength and ARI score

Table 3.5 Pearson correlation test for bond strength and ARI score by group and pooled data

Group	N	Pearson correlation	P value
1	30	0.152	0.421
2	30	0.259	0.167
3	30	0.355	0.054
4	30	0.444	0.014
5	30	0.152	0.424
6	30	0.285	0.126
Grouped data	180	0.298	0.000

Key:

Group 1	Etch, Primer and APC Victory© brackets
Group 2	SEP and APC Victory© brackets
Group 3	Etch, Primer and APC Clarity© brackets
Group 4	SEP and APC Clarity© brackets
Group 5	Etch, Primer and APC Transcend© brackets
Group 6	SEP and APC Transcend© brackets

Pearson correlation test, as shown in Table 3.11 above, was used to test for possible correlations between mean shear bond strength and ARI scores. Overall for grouped data there was a significant correlation between the two variables, with $p < 0.01$. When broken down by group, significant correlation is shown only by Group 4, Clarity© brackets bonded with SEP, $p = 0.014$.

The larger sample size in the grouped data test reduces the effects of variance. The presence of outliers is more significant when sample size is small, as for individual groups where $n = 30$. However when the data is pooled, making $n = 180$, the presence of outliers is diluted, resulting in greater correlation between shear bond strength and AR score.

The results shown in Table 3.11 suggest the presence of a ‘sticking threshold’. This is to say that above a certain shear bond strength there is likelihood that adhesive will remain on the enamel surface following removal of the bracket. This appears to occur between the means of Group 6 (12.437 MPa) and Group 3 (15.96 MPa). Table 3.3 shows the greatest number of ARI score of 3 in Groups 1 and 3, where ‘all adhesive is left on the tooth, with a distinct impression of the bracket mesh’.

3.4 Multiple chi squared (χ^2) analysis of ARI scores

Table 3.6 χ^2 values for a cross tabulation of ARI scores (Degrees of freedom (df))

Group	**1**	**2**	**3**	**4**	**5**	**6**
1		12.57 (29)	21.41 (29)	13.18 (29)	14.42 (29)	13.29 (29)
2			18.80 (29)	12.18 (24)	18.45 (27)	15.08 (26)
3				20.24 (28)	16.84 (27)	17.26 (27)
4					11.65 (22)	16.32 (25)
5						15.33 (24)

Key:

χ^2 values for $p < 0.05$

df	χ^2
22	33.92
23	35.17
24	36.42
25	37.65
26	38.89
27	40.11
28	41.34
29	42.56

Multiple chi squared analysis of ARI score by group shows in Table 3.12 that there is no significant difference in ARI score by group.

Chapter 4

Discussion

Chapter 4 – Discussion

4.1 Shear bond strength of metal vs. ceramic brackets

4.1.1 Sample 8, Group 3 (Etch, primer and APC Clarity© series brackets)

4.2 Bond strength testing

4.3 Examination of the enamel surface

4.1 Shear bond strength of metal vs. ceramic brackets

Bond strength of orthodontic brackets has been studied extensively, with a wide range of data and publications available. The ideal orthodontic bond should ensure that the bracket remains attached to the tooth surface for the duration of treatment, withstanding application of forces to achieve tooth movement and functional forces and at the end of treatment the attachment should be easily removed without damage to the tooth surface.

The results of the present investigation showed that all of the test groups had shear bond strengths exceeding a long-accepted clinically acceptable level of 6-8 MPa (Reynolds,1975). The lowest bond strength was Group 2, Victory© series brackets bonded with SEP. Mean shear bond strength for Clarity© series brackets, when bonded with etch and prime, was significantly greater than all other groups. It is questionable whether such high bond strength is needed clinically. However the debond method used in this investigation does not accurately represent the clinical situation. *In vivo* the bracket is squeezed mesio-distally, allowing the bracket to collapse internally and peal away from the enamel surface.

Information provided with the bracket from the manufacturer (3M Unitek) specifies that no special bonding method is required. The results of this *in vitro* investigation would suggest that this recommendation could be amended.

4.1.1 Sample 8, Group 3 (Etch, primer and APC Clarity© series brackets)

Sample number 8, Group 3 (Etch, primer and APC Clarity© brackets) had the highest bond strength of all test samples (23.29 MPa). This sample failed by fracture of the labial enamel surface, shearing away from the underlying dentine, as shown below in Figure 4.1. Figure 4.2 shows the bracket with fractured enamel still *in situ*.

Figure 4.1 Sample 8, Group 3 (Etch, Primer and APC Clarity© series bracket) following debond

Figure 4.2 Sample 8, Group 3 – fractured labial enamel with bonded Clarity© bracket *in situ*

Although this sample needs to be taken in context, a situation similar to this occurring clinically would be catastrophic. Although all samples were examined prior to testing for the presence of enamel cracks or deficiencies, this sample may have failed in this way due to a deficiency being present prior to testing or the sample having desiccated during testing. That being said, enamel fractures are present clinically and therefore a situation such as this could occur clinically at debond.

The design of the Clarity© series bracket aids removal from the tooth surface without damage, by virtue of a wedge cut into the base, running occluso-gingivally. This allows the bracket to collapse internally and be pealed from the enamel, potentially minimizing enamel fracture. Correlation analysis of bond strength and ARI scores was significant only in Group 4 (p = 0.014), which tested Clarity© brackets in association with SEP. Bond strengths for Clarity© series brackets were significantly greater when bonded with separate etch and prime and more than 50% of adhesive remains on the enamel surface after bracket debonded. Bond failure is therefore occurring at the bracket – adhesive interface. These results are in accordance with Mundstock *et al*. (1999), where 75% of their sample of Clarity© brackets tested *in vitro* failed at the bracket – adhesive interface. They reported a possible reduction in the chances of enamel damage with the modification to the Clarity© bracket base since none of their sample teeth showing signs of enamel damage under x10 light microscopy.

Figure 3.2 shows the proportion of ARI scores by test group. The greatest number of ARI score 3 occurred in Groups 1 and 3, Victory© series and Clarity© series brackets bonded with etch and prime. This suggests that in both these groups bond failure took place at the adhesive bracket interface. In clinical terms, excessive adhesive following debond increases the amount of chairside time needed for its removal. However it might also reduce the risk of enamel surface damage due to enamel fracture on bracket removal. However the use of tungsten carbide burs for adhesive removal can also lead to enamel damage. Schuler and van Waes (2003) examined 284 teeth under SEM and reported that 88% had visible grooves in the line angle +/- cervical areas, caused by the tungsten carbide bur.

Bond strengths for Victory© series brackets bonded with SEP were significantly lower than for all other groups. Although they fell within the recommended clinical value (7.08 MPa), this result raises concern over their clinical reliability. However Manning *et al*. (2005) undertook a prospective clinical trial assessing bond failure rates of brackets bonded with SEP and a conventional acid-etch technique. No significant difference was reported in clinical bond failure rates.

4.2 Bond strength testing

Considerable research has been undertaken to examine the *in vitro* shear bond strengths of different orthodontic brackets when bonded to extracted teeth. There are advantages and disadvantages to such testing and its relevance to clinical practice is questionable.

In vitro shear bond strength testing does not exactly replicate the clinical situation; however, it does give an indication of potential or anticipated bond strengths *in vivo*. In reality, potential loading would be complex with the following acting as stresses on the enamel - adhesive and adhesive - bracket interfaces:

- Multi-directional loading during function e.g. eating
- Stress introduced by application of orthodontic force e.g. following ligation of an archwire

Recommendations for standardisation of bond strength testing were made by Fox *et al* (1994). The following problems arise with *in vitro* investigations of this design:

- Enamel surface structure of extracted teeth may differ from *in vivo* due to desiccation during storage
- Correct storage method may not have been accurately followed
- Bracket removal by using shear force only

Although there are limitations to *in vitro* testing of bond strength, studies of this nature have their place in providing data to support future research, whether that is *in vitro* or *in vivo*.

4.3 Examination of the enamel surface

Light microscopy, under x10 magnification, was used to examine enamel surfaces. ARI scores provide a qualitative assessment of the tooth surface after debonding. Alternative methods include quantitative analysis using a miniaturized Boley gauge (Brown and Way, 1978), scanning ruby laser digitizer (Quick *et al*., 1992), non-contacting laser probe (Al Shamsi *et al*., 2007) or a 3D laser profilometer (Lee and Lim, 2008).

The usefulness of obtaining quantitative data for enamel damage and remaining adhesive is questionable in terms of clinical relevance. The questions which should be asked when assessing enamel surfaces post-debond should be:

- Has any damage occurred to the enamel surface?
- If so, is it detectable either by naked eye or light microscopy?
- Has any damage affected the ability to bond to the tooth surface?
- Is any adhesive remaining?
- If so, how long will this take to remove the remaining adhesive at the chairside?

Any assessment of enamel surfaces post-debond needs to take into consideration the factors important clinically, both to the patient and the clinician.

Chapter 5

Conclusions

The following conclusions can be made from the results of this study:

- Use of separate etch and primer provides a significantly greater shear bond strength than SEP alone
- Considerably more adhesive remains on the enamel surfaces following bracket removal when bond strength exceeds 12.4 MPa, than at lower bond strengths

The following suggestion can be made from the results of this study:

- Bonding Clarity© brackets with separate etch and primer provides shear bond strength that may exceed that required in clinical practice and result in excessive adhesive remaining following bracket removal. It may be advisable to bond Clarity© brackets clinically with SEP rather than separate etch and primer.

Chapter 6

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Appendices

Appendix 1

Results for Group 1: Etch, Primer and APC Victory© brackets

SPECIMEN	NEWTONS	MPa	ARI
1	113.08	10.77	3
2	90.08	8.58	3
3	105.16	10.02	2
4	98.21	9.35	1
5	132.6	12.63	1
6	105.01	10	1
7	111.1	10.58	1
8	100.55	9.58	1
9	61.15	5.82	1
10	124.3	11.84	1
11	109.32	10.41	1
12	61.01	5.81	3
13	87.49	8.33	1
14	123.28	11.74	3
15	133.7	12.73	2
16	146.51	13.95	3
17	94.57	9.01	2
18	84.31	8.03	1
19	134.2	12.78	1
20	104.86	9.99	1
21	107.94	10.28	3
22	81.29	7.74	1
23	96.41	9.18	1
24	101.31	9.65	2

25	103.49	9.86	3
26	119.3	11.36	2
27	108.27	10.31	3
28	82.4	7.85	2
29	71.68	6.83	1
30	95.18	9.06	1

Results for Group 2: SEP and APC Victory© brackets

SPECIMEN	NEWTONS	MPa	ARI
1	58.4	5.56	1
2	40.74	3.88	0
3	51.51	4.91	1
4	119.83	11.41	1
5	53.26	5.07	0
6	71.31	6.8	1
7	112.09	10.68	2
8	58.86	5.61	1
9	50.76	4.83	1
10	38.5	3.67	1
11	119.01	11.33	0
12	82.34	7.84	1
13	40.48	3.86	1
14	58.92	5.61	0
15	31.86	3.03	1
16	78.54	7.48	1
17	116.47	11.09	1
18	91.51	8.72	1
19	85.64	8.16	1
20	49.63	4.73	0
21	58.41	5.56	1
22	57.94	5.52	1
23	82.63	7.87	1
24	65.91	6.28	0
25	95.63	9.11	1
26	120.16	11.44	1

27	109.65	10.44	1
28	54.86	5.22	0
29	91.4	8.7	0
30	61.28	5.84	0

Results for Group 3: Etch, Primer and APC Clarity© brackets

SPECIMEN	NEWTONS	MPa	ARI
1	152.57	10.28	0
2	253.3	17.05	1
3	37.76	2.54	1
4	273.72	18.44	3
5	168.46	11.35	1
6	228.68	15.41	3
7	196.67	13.25	3
8	345.36	23.29	3
9	323.63	21.81	1
10	330.37	22.26	0
11	189.5	12.77	1
12	207.7	13.99	0
13	308.68	20.8	0
14	282.59	19.04	1
15	303.85	20.48	2
16	278.85	18.79	3
17	211.1	14.23	1
18	149.61	10.08	2
19	314.02	21.16	3
20	296.75	19.99	2
21	185.2	12.48	1
22	132.09	8.9	1
23	340.95	22.98	3
24	302.56	20.39	3
25	241.74	16.29	1
26	178.38	12.02	1

27	103.21	6.95	1
28	245.9	16.57	2
29	236.81	15.96	2
30	298.54	19.24	2

Results for Group 4: SEP and APC Clarity© brackets

SPECIMEN	NEWTONS	MPa	ARI
1	78.74	5.31	1
2	215.18	14.5	1
3	177.62	11.97	0
4	131.59	8.87	0
5	150.98	10.17	0
6	159.8	10.77	1
7	112.11	7.55	0
8	154.21	10.39	1
9	168.45	11.35	1
10	137.77	9.28	1
11	173.09	11.66	0
12	197.34	13.29	1
13	265.74	17.91	0
14	222.62	15.0	1
15	265.07	17.86	2
16	98.1	6.61	0
17	239.78	16.16	1
18	155.61	10.49	1
19	203.37	13.7	1
20	164.58	11.09	0
21	139.82	9.42	1
22	192.38	12.96	1
23	124.73	8.4	1
24	151.6	10.22	0
25	119.13	8.03	0
26	83.2	5.61	0

27	261.89	17.65	1
28	186.31	12.55	1
29	177.65	11.97	1
30	109.67	7.39	0

Results for Group 5: Etch, Primer and APC Transcend© brackets

SPECIMEN	NEWTONS	MPa	ARI
1	60.01	7.26	0
2	41.67	5.03	1
3	62.16	7.51	1
4	107.66	13.0	0
5	89.52	10.81	0
6	51.55	6.22	1
7	90.6	10.94	1
8	72.06	8.7	0
9	71.57	8.64	0
10	61.37	7.41	1
11	80.31	9.69	0
12	90.11	10.88	2
13	142.92	18.11	0
14	116.84	14.11	1
15	29.2	3.53	1
16	101.67	12.28	0
17	68.67	8.29	0
18	91.82	11.1	1
19	76.53	9.24	1
20	138.47	16.72	1
21	129.6	15.65	1
22	51.29	6.19	0
23	109.28	13.2	1
24	122.67	14.82	1
25	89.25	10.78	0
26	67.41	8.14	0

27	53.98	6.52	0
28	96.28	11.63	1
29	114.6	13.84	1
30	137.5	16.61	1

Results for Group 6: SEP and APC Transcend© brackets

SPECIMEN	NEWTONS	MPa	ARI
1	78.51	9.48	0
2	51.36	6.19	0
3	121.03	14.62	1
4	168.1	20.3	0
5	123.24	14.88	1
6	58.53	7.07	0
7	139.64	16.86	1
8	111.95	13.52	0
9	94.99	11.47	1
10	69.94	8.45	1
11	68.51	8.27	1
12	63.47	7.67	1
13	164.95	19.92	0
14	91.25	11.02	0
15	143.67	17.35	1
16	159.62	19.28	1
17	118.73	14.34	1
18	105.64	12.76	0
19	74.91	9.05	1
20	86.73	10.47	0
21	64.67	7.81	0
22	96.27	11.63	1
23	52.63	6.36	0
24	128.34	15.5	1
25	137.58	16.62	1
26	59.23	7.16	0

27	110.26	13.32	1
28	133.81	16.16	1
29	106.49	12.86	1
30	105.34	12.72	1

Appendix 2

Data for Method Error Calculation

Test Group	Sample Number	Original ARI Score	Re-score (ARI)
5	12	2	2
6	24	1	1
4	21	1	1
2	15	1	1
6	7	1	0
4	21	1	1
3	27	1	0
1	13	1	1
5	1	0	0
6	10	1	1
2	6	1	1
5	13	0	0
6	18	0	1
6	24	1	1
2	11	0	0
2	29	0	0
1	5	1	1
4	16	0	1
6	6	0	0
5	30	1	1
6	27	1	1

5	22	0	0
5	25	0	0
5	5	0	0
2	9	1	1
6	17	1	1
1	19	1	1
1	30	1	1
5	14	1	1
3	1	0	1

Dahlberg method error calculation:

$ME = \sqrt{} (\sum d^2 / 2n)$

Where:

d = Difference between 1st and 2nd readings

n = number of samples