"THE DEVELOPMENT OF AN ADJUSTABLE ORTHODONTIC BRACKET"

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Discipline of Orthodontics Faculty of Dentistry, University of Sydney, Australia
DECLARATION

CANDIDATE CERTIFICATE

The work presented in this thesis is, to the best of my knowledge and belief, original except as acknowledged in the text. I hereby declare that I have not submitted this material, either in full or in part, for a degree at this or any other institution.

Signature: [Signature]
Date: 18/5/07
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Outline of the Thesis

The thesis is divided as follows:

Chapter 1: Background to Research

Chapter 2: Literature Review

Concentrating on bond strength and factors affecting bond strength

Chapter 3: Assessment of Bonding Accuracy

Chapter 4: Designing and Testing of the Prototype Bracket

Chapter 5: Future Directions
CHAPTER 1 BACKGROUND TO RESEARCH

Introduction

To effectively plan where you would like to go often requires knowledge of where you came from. The design of a new orthodontic bracket is no exception and a brief history of our predecessors seems an apt way to commence the introduction. This section will briefly discuss the history of the orthodontic bracket. It should be remembered that some of the basic principles for orthodontic tooth movement were known 2000 years ago yet it was not until the 18th Century when organised orthodontics began to emerge. The early appliances were based on the “bandeau”, a horseshoe shaped strip of precious metal to which the teeth were ligated, first described by Pierre Fauchard in 1728 in his 2-volume book “The Surgeon Dentist: A Treatise on the Teeth”. As we moved into the 19th Century, instead of ligating the expanded bar directly to the teeth ligation attachments were developed beginning with cap crowns (Delbarre, 1815), clamp bands (Schange, 1841) and finally cemented bands (1870) following Magill’s invention of an oxychlorid of zinc cement\(^1\). Even at this stage the bands were used to anchor the crude expansion devices to which the teeth were ligated. Dr Evans was the first to attach buccal tubes to clamp bands, into which the labial arch wire was placed\(^2\). It is from here that orthodontic brackets began to emerge as attachments to teeth to effect their movement.
Edward Angle

Orthodontic innovation in the late 1800’s and early 1900’s belonged to Edward Hartley Angle. His contribution to the practice of orthodontics in terms of diagnosis and treatment planning as well as in appliance innovation resulted in him being referred to as the “father of modern orthodontics”.

He graduated from dental school in 1878 and experienced many technical problems and frustrations with the typical orthodontic appliance of the time, which consisted of a rigid framework to which the teeth were tied so that they could be expanded to the arch form dictated by the appliance. His first appliance, the E-Arch (1887), was an improvement on this design and was presented to the 9th International Medical Congress, having decided that 3 movements were necessary (1) pushing, (2) pulling and (3) twisting. The appliance was composed of a number of basic components. The components were mass-produced to enable assembly into a simple, stable, efficient, delicate and inconspicuous treatment device, in less time and with minimal pain and discomfort to the patient. This enabled practitioners to treat more patients at a higher level of excellence and at a lower cost than before.

The basic E-arch consisted of clamp bands on the molar teeth, and a heavy labial arch wire extended around the arch (Figure 1.1). The end of the wire was threaded and a small nut was placed on the threaded portion of the arch allowing the wire to be
advanced so that the arch perimeter increased. Individual teeth were ligated to this expansion arch. The heavy archwire was supplied in four different designs, depending on the treatment planned.

(1) The basic E-arch was used in the mandible with Baker anchorage (class II elastics).

(2) Ribbed E-Arch was used with expansion and by tying brass ligatures around the teeth to the arch.

(3) Modified E-Arch without threaded ends that fit into the molar sheaths was use with an attached ball for high pull headgear in the incisor area. The protruding anterior maxillary teeth were retracted into spaces provided by the extraction of permanent first molar teeth using the headgear and elastic traction. The E arch would slide through the sheath as the teeth retracted.

(4) An E-arch with hooks on the upper arch located in the canine region, for the attachment of class II elastics to move the entire maxillary dentition distally and the mandibular dentition mesially.
Dr. Angle realized the inadequacy of the E-Arch control three-dimensional movement and introduced the pin and tube appliance in 1910 (Figure 1.2). This was the first appliance developed by Angle to effectively move the teeth bodily. The system consisted of a small vertical tube soldered to a band that was cemented to the tooth to be moved. An archwire was then adjusted to approximate the incisal openings of the tubes. Small pins were then soldered onto the alignment wire and used to engage the tubes on the bands. Changes in the angulation of the pin, labial or lingual, mesial or distal resulted in bodily movement of the tooth. This technique required a high degree of skill to obtain perfect positioning between the tubes, pins and the archwire. It was also necessary to unsolder the pins every time it was desired to move teeth to a
different location. The ideal E-arch had to be sacrificed so that each tooth could be moved by the pin and tube attachment. The arches were altered as the tooth movement progressed to an ideal arch form. The pin and tube appliance was such a difficult appliance to use it was said that only Angle had the technical ability to use it. It was also difficult to obtain rotation correction with this design.

Figure 1.2   Pin and Tube Appliance

(Reproduced from Orthodontics, Current principles and techniques, third edition, Graber T, M and Vanarsdall R, L. p651, Mosby, USA)

These difficulties led Angle to develop the ribbon arch appliance in 1915 (Figure 1.3). The ribbon arch consisted of a modification of the tube so that it provided a vertical rectangular slot behind the tube opening occlusally. The ribbon arch was 0.10
x 0.20 inches gold wire and initially conformed to the malocclusion, held in place in the brackets with a brass pin. The appliance allowed the teeth to slide freely mesiodistally, which allowed for space closure. It was an immediate success perhaps due to the good spring qualities of the ribbon wire, which allowed for efficient aligning of malposed teeth. Rotation of the teeth and positioning of the roots were achieved by bending the rectangular archwire so that when it engaged the parallel walls of the bracket it would generate a force to move the tooth in the desired direction. However en masse movement of teeth was necessary for a significant number of patients, a movement for which the ribbon arch appliance was not generally suitable. Anterior teeth could only be retracted at the expense of the anchorage provided by the posterior teeth, mesial and distal tipping bends could not be incorporated into the arch wire and the premolar teeth could not be moved bodily.
The span between the first premolar and the first molar tube was too short to permit placement of the stiff arch wire and its friction sleeve nut into the tube and the vertically directed premolar slot. To overcome these difficulties Angle redesigned the appliance, reorientating the slot from the vertical to the horizontal. The rectangular wire was now rotated 90 degrees to the orientation of the ribbon arch establishing the “edgewise” bracket (1928)(Figure 1.4). The edgewise bracket had
flanges extending occlusally and gingivally, which allowed the archwire to be tied in with ligatures (initially brass and later stainless steel). The dimensions of the slot were altered to 0.022 x 0.028 inches with a 0.022 x 0.028 inches precious metal wire used. This new archwire-bracket interface allowed the tooth to be moved in 3 planes simultaneously. This was accomplished by placing bends in the archwire (Figures 1.5, 1.6, 1.7).

Figure 1.4  The Edgewise Bracket

(Reproduced from Orthodontics, Current principles and techniques, third edition, Graber T, M and Vanarsdall R, L. p653, Mosby, USA)

The narrow width of the bracket resulted in inefficient rotation control. To overcome this problem gold eyelets were soldered in appropriate positions on the band and ligature wires tied from the eyelets to the archwire, thus deflecting the archwire and providing rotation control. The eyelets needed to be tied for the remainder of the treatment to prevent relapse of the rotation.
The three planes of control were:

(1) First order (in-out)
- The first order bends are offsets in the arch wire to accommodate the labiolingual and buccolingual thickness of teeth. They may also be used to produce horizontal forces for overcorrection.

(2) Second order (tip)
- Second order bends are offsets in the archwire in the vertical plane for tipping and uprighting teeth.

(3) Third order ("torque")
- Third order bends are a "twist" in a rectangular arch along the long axis of the archwire producing "torque" or root/crown movement bucco-lingually.
Figure 1.5  First order bends (in-out)

(Archwires viewed from the occlusal demonstrating the bends necessary to accommodate the labiolingual and buccolingual thickness of the teeth.)

Upper Arch wire  Lower arch wire

Figure 1.6  Second order bends (Tip)

(Reproduced from Fixed Orthodontic Appliances, Principles and Practice, Williams J, K, Cook, PA, Isaacson, K, G, Thorn, A, R, p 16, Wright, Butterworth-Heinemann, UK. The diagram demonstrates second order bends creating the correct tip of the upper four anterior teeth.)
Figure 1.7 Third order bends ("Torque")

(Reproduced from Fixed Orthodontic Appliances, Principles and Practice, Williams J, K, Cook, PA, Isaacson, K, G, Thom, A, R, p 16, Wright, Butterworth-Heinemann, UK. The figures demonstrate the "distortion" of the rectangular archwire necessary to create labial and buccal root "torque")

The edgewise bracket was by no means the only bracket available and there were many innovators attempting to improve the efficiency of tooth movement. The
Johnson twin-wire appliance was published in 1934. It was one of the first appliances to incorporate light wires that delivered forces physiologically favourable to the tissues. It consisted of two light, round archwires 0.011 inches in diameter. The Johnson bracket consisted of a male and a female part. The male part was welded to the middle of the band, parallel to the edges and at right angles to the long axis of the tooth. It had parallel walls, which formed a channel into which the twin wires were seated. The female cap slipped over the male part and was held in with friction. When the twin wire was placed in the brackets it automatically formed the shape of a normal dental arch without any bending or manipulation. When the teeth were moved into their correct position, all of the brackets would lie in the same plane. One drawback of the twin-wire appliance was it was difficult to position the teeth in the third order.

In 1937 Spencer Atkinson introduced the Universal bracket. It was termed the Universal bracket as it allowed for practically every type of tooth movement. It had two transverse slots for labial wires. The gingival slot was smaller and allowed for the placement of a round wire 0.010 or 0.012 inches in diameter. This was approximated to the archform, but had no further bends placed. It was used to intrude/extrude teeth and to make their roots upright mesiodistally. The incisal slot had a flat wire 0.010 x 0.028 inches. This was used to stabilise the teeth while the gingival wire induced tooth movement. It also allowed for rotation control and buccolingual uprighting. The wires were held in place by a single lock pin.
In 1956\textsuperscript{9} Begg introduced the differential force (or light wire) technique, which was a system based on the ribbon arch bracket, turned gingivally (Figure 1.8). A single, round stainless steel wire was utilized, supplied by Arthur J Wilcock, Director of metallurgical research at the University of Melbourne, Australia. He had met Begg in the 1940's and after many years of research and development had produced a cold drawn, heat treated wire that provided a balance between hardness and resilience with zero stress relaxation that Begg required to open deep anterior open bites, control arch form and provide molar control. At this stage the technique did not include detailed finishing.

However when Begg returned to present to the American Association of Orthodontists in 1960 he had reorganised his technique to facilitate teaching and learning. He had divided the technique into three stages with definite objectives for each stage, introduced uprighting springs and root torquing auxiliaries so that the finished cases could not be discerned from similar cases treated with edgewise mechanism\textsuperscript{10}. 

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Further developments of the Edgewise bracket

The problem of the lack of rotation control with the original edgewise bracket and the time consuming tying of the eyelets was overcome in 1949 by Dr B Swain\textsuperscript{11} who placed 2 brackets on a single tooth. The two brackets were spaced so they could rotate the tooth without the need for eyelets. This was the first “Siamese twin bracket”, later called the twin bracket. It gained immediate popularity due to its ability to correct and maintain rotations and axial tooth inclinations. The twin bracket did not induce tooth movement but allowed deflection of the archwire over a broader area of the tooth, enabling the archwire to facilitate the rotation. Highly resilient round wires were used to engage the twin bracket in the initial stages of treatment.
effecting as much tooth movement as possible. However, the reduction of the interbracket distance had an adverse effect on the resilience of the archwire and limited the amount of space for closing loops and second order bends.

In 1949\textsuperscript{12} Lewis solved the problem of rotation control by maintaining the original Angle/Edgewise bracket and adding two soldered auxiliary rotation arms, which acted as lever arms to deflect the wire and rotate the tooth. This maintained the interbracket span whilst not interfering with closing loops or second order bends. The arms could also be bent to overcorrect rotations by differential differential activation and deactivation of the rotation wings.

Figure 1.9  The “Lewis” Bracket

Bracket placement and modification of the bracket slot

Bracket placement on the band was always deemed important, initially being positioned in the centre of the band and then later a measured distance from the incisal edge. The slot was orientated parallel to the occlusal surface (perpendicular to the long axis of the tooth). Angle in 1929 \textsuperscript{13} suggested that tipping the brackets on the band was a good method of reducing the vertical bends (second order bends) in the arch wire. This tipping of the brackets on the band was further emphasised by Holdaway in 1952\textsuperscript{14} to reduce procedures in arch wire fabrication, which are difficult to reproduce in subsequent arch wire changes, i.e. copying bends. As an additional modification, Ivan Lee milled “torque” into the bracket face. Jarabak and Fizzell demonstrated a modified edgewise technique which incorporated second- and third-order mechanics (tip and torque) in the appliance at the 1960 meeting of the American Association of Orthodontists, but they felt that only the technology of the time prevented the incorporation of first order mechanics\textsuperscript{15}.

This steady move to build the treatment into the bracket and reduce or eliminate the time consuming first, second and third order bends was finally achieved in the early 1970’s by Andrews. He studied 120 models of untreated ideal dentitions. Six significant characteristics were found to be consistent within this group which were designated as the “six keys for normal occlusion”\textsuperscript{16}.
Andrews incorporated the six keys into the appliance leading to the development of the Straight-Wire appliance\textsuperscript{17,18}. This preadjusted appliance had incorporated into it control of tooth movement in three planes of space (Figures 1.10-1.12)\textsuperscript{19}. In theory, in an ideal gnathological set up for a given patient, the bracket bases would fit accurately at a predetermined point and the bracket slots would passively accept the straight wire coordinated for the patient’s arch form\textsuperscript{20}.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure10.png}
\caption{Elimination of first order bends}
\end{figure}

Figure 1.11  Elimination of second order bends


![Diagram of Standard Edgewise and Preadjusted appliances for second order bends]

Figure 1.12  Elimination of third order bends ("torque")


![Diagram of Standard Edgewise and Preadjusted appliances for third order bends]
Definition: The Long Axis of the Clinical Crown (LACC) ²¹

(1) Viewed from the buccolabial perspective: For molars the LACC is identified as the dominant vertical groove on the buccal surface. For all other teeth it is the vertical mid-developmental ridge, the most prominent portion of the central area of the buccolabial surface.

(2) Viewed from the mesiodistal perspective, the LACC is represented as a line tangent to the middle of the crown’s labial or buccal surface. For molars it parallels the dominant groove. For all other teeth it parallels the mid-developmental ridge.

Definition: The Long Axis point (LA-point) ²¹

The mid-point of the LACC, as the crown has no obvious horizontal axis or equator it is judged as you would select the mid-point on a 5 millimetre line (Figure 1.13).
Figure 1.13 The LA-point

(Modified from Andrews, L, A: The Straight-Wire

Upper left central incisor

The Straight-Wire system is dependent upon specific, reliable, locatable bracket sitting points (LACC and the LA-point) and specific design features:

- third order built into the base of the brackets
- a base contoured vertically as well as horizontally
- tip built into the brackets
- in-out built into the brackets
- an offset built into the molar tube
The success of the Straight-Wire appliance relies on ideal bracket placement\textsuperscript{22}. The widespread use of the appliance since its introduction over 30 years ago has allowed orthodontists to achieve good results for their patients with greater efficiency and effectiveness\textsuperscript{23}. There is a gradual progression towards finishing rather than an abrupt stage of wire bending\textsuperscript{24}. However even if the brackets are positioned correctly and the tip, "torque" and in-out compensations built into the appliance are suited to the patient's dentition it will probably still be necessary to place detailing bends\textsuperscript{25}. There are several factors that may increase the amount of detailing necessary\textsuperscript{26}:

(1) Inaccurate bracket placement

(2) Variations in tooth structure, such as irregular facial surfaces, crown-root angulations and unusual crown shapes.

(3) Variations in vertical and anteroposterior jaw relations will prevent compensatory changes in second and third order inclinations, necessary to idealise occlusal relationships.

(4) Mechanical deficiencies of the appliance:

- Play between the arch wire and arch wire slot.
- Force application is located away from the centre of resistance. Consequently when a force is applied to a tooth additional forces are also produced. For
example intrusive forces on incisor teeth may result in lingual root torque.

- Force diminution: A minimum threshold of force is required to move a tooth and as the arch wire returns to its original shape the applied force reduces. If the force lies below the minimum threshold, the straight wire may never quite straighten completely.

(5) Overcorrection may be necessary.

In addition it has been shown that the LA points are not necessarily on the same plane\textsuperscript{27,28} and this has led to additional recommendations for ideal bracket placement. McLaughlin and Bennett (1995)\textsuperscript{28} advocated the positioning of brackets at a measured distance from the incisal edge, with different vertical positions recommended for different sized teeth. They indicated that the use of a Dougherty height gauge, to check the vertical position of the brackets, reduced the errors in the vertical dimension with a 50-60 per cent reduction in the need to reposition brackets. Kalange (1999)\textsuperscript{29} recommends a marginal ridge method, whereby brackets are placed indirectly using the marginal ridges of the posterior teeth as reference points.

**Inaccuracy of Bracket placement**

Two questions need to be answered:

(1) How accurate is bracket placement?

(2) If the brackets are positioned correctly is there a need for detailing bends?
Regardless of which method is used for the positioning of brackets there seems to be some margin of deviation from the ideal location before operator error is factored into the equation. Measuring from the incisal edge and positioning at the LA-point has been shown to be inaccurate for premolars and can lead to marginal ridge discrepancies between the premolars and molars and a lack of occlusal contacts with the opposing dentition. Fukuyo et al. (2004) analysed digitised models of 40 patients with normal occlusions and compared three different methods of positioning brackets (LA-point method, height method and marginal ridge method). The bracket positions relative to a constructed virtual bracket plane were determined and even if the brackets were positioned ideally for each technique vertical errors still occurred.

Andrews hypothesised that to satisfy gnathology's demanding standards, we must work within error limits of 2° in tip, 2° in torque and 0.5 mm vertically. He asked 54 orthodontists to draw pencil lines, estimating parallelism, midpoints and angles. The individual results demonstrated that parallelism and midpoints were much easier to estimate than angles. However he points out that (tip and “torque”) is already built in to the Straight-Wire appliance.

One possible source of bracket positioning error is the perception of the defined landmarks and this was demonstrated by Fowler (1990) who asked 71 clinicians to mark the LACC and LA point on a plaster cast (upper right premolar to central incisor). He found that the greatest error in the LACC angulation, less for LA point.
height and least for LA point mesiodistal positioning. Recent training reduced intra-
and inter-clinician variability. Similar results were found by Taylor and Cook
(1992)\textsuperscript{33} who asked twelve clinicians to place straight-wire brackets at the mid-point
of the clinical crown on the six anterior teeth of a crowded typodont (upper left
canine to right canine). They also demonstrated that the error in angulation was the
greatest and the mesiodistal error the least. Many of the operators were unable to
consistently angulate the brackets within a 2° limit.

Balut et al.\textsuperscript{34}(1992) found discrepancies in height and angulation with a mean of
0.34\text{mm} (sd 0.29) for the linear measurements and a mean of 5.54° (sd 4.32°) for the
angular measurements between bracket pairs for all faculty members. They concluded
that the error in bracket placement seems more related to the skill of the operator,
tooth structure, size of the clinical crowns and malposition of the tooth in the dental
arch.

Inaccuracy has also been demonstrated when measuring from the incisal edge using a
Boone height gauge. Koo et al (1999)\textsuperscript{35} compared direct and indirect bonding and
found both techniques failed to execute ideal bracket placement. The errors are shown
in the Table 1.1.
Table 1.1  Mean and standard deviations of bracket positioning error

(Koo et al.1999)\textsuperscript{35}

<table>
<thead>
<tr>
<th></th>
<th>Height (mm)</th>
<th>Mesiodistal (mm)</th>
<th>Angulation (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
</tr>
<tr>
<td>Direct</td>
<td>0.35</td>
<td>0.6</td>
<td>0.19</td>
</tr>
<tr>
<td>Indirect</td>
<td>0.31</td>
<td>0.25</td>
<td>0.18</td>
</tr>
</tbody>
</table>

Despite the large number of cases treated there is limited clinical reporting on bracket accuracy. Aguirre et al (1982)\textsuperscript{36} using a split mouth technique measured the accuracy of direct and indirectly positioned brackets for 11 patients. For each tooth there was one linear measurement to identify the vertical position of the bracket and one angular measurement to identify the bracket’s variation from the considered ideal of 90 degrees. They found that neither technique proved 100 per cent accurate for the linear or angular measurements with the operator having more difficulty in assessing angulation than height, confirming what had been demonstrated from the typodont studies. Overall brackets were placed within 0.7mm from ideal and within 1.3 degrees of the ideal angulation of 90 degrees. There was a trend for left side bonds to be more accurate in the upper arch and right side bonds to be more accurate in the lower arch, suggesting a basic limitation in bracket positioning. Hodge et al. (2004)\textsuperscript{37}
using a split mouth design compared the accuracy of direct and indirectly bonded brackets, positioning the brackets with a height gauge. In contrast to other studies they found that vertical errors were the greatest with angular errors the least. There was no statistically significant difference between the two methods in mean bracket placement errors (Table 1.2). The authors concluded that the indirect technique reduced the envelope of error in all three directions examined, however the vertical errors are outside of those recommended by Andrews.

Table 1.2 Mean and standard deviations of bracket positioning error
(Hodge et al. 2004 37, where a minus value indicated gingivally or distal positioning)

<table>
<thead>
<tr>
<th>Height (mm)</th>
<th>Mesiodistal (mm)</th>
<th>Angulation (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean</td>
<td>SD</td>
</tr>
<tr>
<td>Direct</td>
<td>-0.27</td>
<td>0.46</td>
</tr>
<tr>
<td>Indirect</td>
<td>-0.20</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Therefore in conclusion clinical and typodont studies have shown that bracket positioning is inaccurate and even if they are placed accurately detailing bends or repositioning of the brackets will be necessary.
Bracket repositioning

Repositioning of the bracket requires removal of the bracket and the adhesive. This may adversely affect the treatment in one of two ways:

(1) Increasing the amount of enamel loss, potentially increasing the risk of enamel scarring. Many investigations have focused on the available debonding techniques to determine which one leaves the tooth with the best finish without removing an excessive amount of tooth structure. Loss of enamel at clean up can be between $55.6\mu m^{38}$ to $149.87\mu m^{39}$ and is largely dependant on the method of adhesive removal.

(2) Reduced bond strength of the rebonded bracket, increasing the risk of bracket debonding. This increases the number of brackets used (unless they are reconditioned), increases the clinical time, which reduces efficiency and cost effectiveness of treatment. Two aspects of rebonding need to be considered: (1) Clean up of the enamel surface and (2) Whether a new bracket is used or the old one reconditioned. Mui et al. (1999)\textsuperscript{40} found no significant difference in bond strength after reconditioning the enamel surface with a tungsten carbide bur. However in contrast Bishara et al.(2000)\textsuperscript{41} found that the initial shear bond strength was the greatest with lower and inconsistent shear bond strengths on
subsequent rebonding twice. They suggested this was due to islands of adhesive remnants, which cannot be seen with the naked eye. *In vitro* studies are contradictory with some reporting a reduction in bond strength\textsuperscript{42} when a reconditioned bracket is used and others\textsuperscript{43,44} finding no difference. Clinically Kinch *et al.* (1988)\textsuperscript{45} found that 10\% of second and third time bonds fail in 4-5 weeks whereas only 2\% of first time bonds during the same period.

Therefore one can conclude that repositioning a bracket increases the risk of enamel damage and increases the cost, either in use of additional materials or in increased clinical time.
The inadequacies of the current systems could be overcome by:

(a) Modifying an existing adhesive so that it maintained its bond strength but could be softened then rehardened allowing the bracket to be manipulated (repositioned) without any risk of damage to the enamel surface and dental tissues.

(b) Developing a new bonding material that provided sufficient bond strength but could also be softened then rehardened allowing the bracket to be manipulated (repositioned) without any risk of damage to the enamel surface and dental tissues.

(c) Adding an intermediate layer between the adhesive and the bracket, which can be softened then rehardened allowing the bracket to be manipulated (repositioned) without any risk of damage to the enamel surface and dental tissues.

(d) To create a new bracket that can be repositioned on the tooth surface. That is a two-part bracket consisting of a base and a movable face. The face can be manipulated with the base remaining in the same position.
References:


33. Taylor NG, Cook, PA. The reliability of positioning pre-adjusted brackets: An in


2000;70:435-441.


Chapter 2 Literature Review

Introduction

Orthodontic devices should interfere minimally with the patient’s comfort appearance and hygiene. The use of higher strength cements and resin adhesives allow the use of smaller attachments, which are more patient friendly, as they are more aesthetic and easier to keep clean. However it is essential that the cements and resin adhesives should not be so strong that there is a risk of fracture of the enamel surface on the removal of the attachment.

The advent of newer materials (cements, adhesive resins and hybrid cement-resin combinations) may offer improved physical properties and clinical benefits. Practitioners should have an understanding of the features, benefits and limitations of each material to choose the best material for each clinical situation.

Factors affecting bond strength measurement

The bond strength of orthodontic brackets is of great interest and importance in orthodontics and can be carried out in a number of ways:

*In Vitro:* using a clinical simulation model where extracted teeth are used as substrates. Brackets are either bonded to human teeth prior to their removal or more commonly to already extracted human or bovine teeth. The brackets are then debonded using shear or tension forces. This model appears to be clinically relevant
as both the tooth and the bracket are available for study. However, bond failure occurs at both interfaces (tooth-adhesive and adhesive-bracket) sometimes making it difficult to identify the weakest link.

*In Vitro:* using an isolated surface model where the tooth-adhesive interface can be studied separately from the adhesive-bracket interface. A cone of adhesive is bonded to the tooth and then debonded to study the tooth-adhesive interface. The bracket-adhesive interface maybe studied by bonding the bracket to the adhesive retained on a flat acrylic surface or a well, another bracket or a silanated metal rod. This is especially useful for the study of metal brackets where the bond commonly breaks between the bracket and adhesive.

*In Vitro:* using an alternative synthetic standardised substrate. Brackets can be bonded to the substrate and debonded using shear and tension forces. This use of an artificial substrate, which closely resembles the mineral phase of enamel, may solve the problem of a readily available, reproducible model for enamel adhesion studies.

*In vivo* the retention rates of various brackets and adhesives maybe studied clinically throughout part or all of a completed treatment. The reports can be prospective or retrospective and generally involve comparisons of retention rates of brackets between patients and within patients in a split mouth design. They usually report the mean, standard deviation and statistically significant differences between
the test groups. One of the problems of the percentage of bracket failure being reported is that it doesn’t indicate when the bracket actually failed. Therefore, a better analysis used in some studies is a survival analysis, the Weibull analysis, which emphasises the tails of the distribution and provides a cumulative probability of bracket failure at various points in time during the study\textsuperscript{17}. An alternative type of clinical study uses a dynamometer intraorally to tests the bond strength of the test bracket/adhesive\textsuperscript{18}.

The units of bond strength may be reported as megapascals (MPa), kilograms per square centimetre (kg/cm\textsuperscript{2}) and pounds per square inch (lb/in\textsuperscript{2} or psi). However it is common to see the bond force reported in units of Newtons (N), kilograms (kg) or ponds (lb). The bond strength is the bond force divided by the surface area of the bonded interface. On average the surface area of a bracket is $16$ mm\textsuperscript{2}, with the average force due to mastication being between $40$ and $120$ N\textsuperscript{19}. Therefore a typical bracket should be able to withstand an applied stress of 6-8 MPa\textsuperscript{20}.

The most common studies are laboratory studies and they are an important preliminary step to indicate if a new technique, adhesive or bracket will perform successfully clinically. To evaluate the bond strength, laboratory studies have used a variety of tests, methods and conditions to measure the stress necessary to break the bond\textsuperscript{21}. The method can be chosen to reduce the potentially distorting influence of confounding factors. However, due to the large number of tests and potential
variables it has been suggested that orthodontic bond testing should be universally standardised to allow more legitimate comparisons between products and approaches\textsuperscript{22-24}. The bond strength of a material is generally tested in shear, tension, torsion or peeling using either a screw driven or a servohydraulic universal testing machine. The following are a list of potential variables that may affect the bond strength:

(A) Type of adhesive used.

(B) Thickness of adhesive.

(C) Preparation of tooth surface.

(D) Contamination of the tooth surface.

(E) Type of tooth (incisor, molar, human, bovine).

(F) Substrates chosen for bond testing.

(G) Fluoride content of the tooth.

(H) Disinfection and storage media of tooth before bonding.

(I) Elapsed time following bonding.

(J) Configuration of specimen testing jig/ type of loading

(K) Crosshead speed of mechanical testing machine

(L) Bonded area of the bracket/ bracket base

(M) Type of bracket

(N) Light curing unit

(O) Other methods of accelerating the setting time

(P) Repeated bonding
(A) Type of adhesive used

The development of adhesives to successfully bond orthodontic attachments directly to teeth has been greatly influenced by research directed towards improving properties of materials used for conservative dentistry. Newer orthodontic cements, adhesive resins and hybrid cement-resin combinations offer improved physical properties and clinical benefits, but there are clear differences in the clinical indications and contraindications for each class of material. The available adhesives can be divided by method of cure (chemical, light, dual or thermal) or type of material. Essentially there are three types of material used to directly bond orthodontic brackets:

(1) Resins
(2) Cements
(3) Hybrids

(1) Resins

There are two groups of resin adhesives used for direct bonding:

(a) Acrylic resins.

(b) Diacrylate resins.

The acrylic resins are based on the self-curing acrylic resins, which were developed in the 1940’s by German chemists. They consist of methyl methacrylate monomer and an ultra fine polymer powder, usually activated by a tertiary amine benzoyl...
peroxide curing system or tri-n-borane. They have a large coefficient of expansion and a volumetric contraction on curing of 6-10%; however, the film thicknesses used in direct bonding are thin and therefore the side effects are minimised. They are available as filled or unfilled resins\textsuperscript{20}.

The diacrylate resins include epoxy resins and dimethacrylates. The epoxy resins were used by Newman (1964\textsuperscript{26}, 1965\textsuperscript{27}) and Cuerto\textsuperscript{28} and were possibly the first successful adhesives used for direct bonding. There is some conjecture as to whether zinc phosphate was the first cement used for direct bonding\textsuperscript{29}. However with the cyanoacrylates some patients had allergic reactions, it had a long cure time, poor dimensional stability and proved inadequate for the oral environment. The most commonly used diacrylate cement is bisphenol-A-glycidyl-dimethacrylate (Bis-GMA) developed by Bowen in 1962. It is cured either chemically with tertiary amine-benzoyl peroxide (as with the acrylic resins), by light using camphorquinone, which is sensitive to light in the blue region (450-500 nm) of the visible light spectrum, with the peak activity centred around 480 nm or by a combination of chemical and light (dual cure).

Optimal adhesion with resin adhesives requires a dry operating field and the preparation of the tooth surface by acid etching\textsuperscript{30} or other surface treatments. Etching with phosphoric acid has a number of effects on the enamel surface. The resin flows into porosities and results in the presence of retentive tags, which bond the resin mechanically to the etched enamel surface. The etching, washing and drying of the
enamel results in high surface energy, which can be wetted by the resin; however, it is technique sensitive and if there is moisture contamination most of the porosities become plugged resulting in impaired penetration, educed length and an insufficient number of resin tags\textsuperscript{31}. Moisture contamination is the most common cause of bond failure\textsuperscript{32}.

The amount of filler content may affect the bond strength of orthodontic brackets. Buzzita \textit{et al.} (1982)\textsuperscript{33} compared unfilled (Bond-Eze), low filled (Endur, 28%), and highly filled (Solo-Tach, 55%) resins with three types (polycarbonate, stainless steel and ceramic) of brackets. They found that the highest bond strength was achieved with the highly filled diacrylate resin for the metal bracket but the plastic and ceramic brackets performed best with the unfilled acrylic resin. They suggested that the adhesive needs to be selected to match the bracket used to maximise bond strength. The authors suggested the unfilled resin might result in greater penetration into the retentive areas of the ceramic brackets. In contrast, Osterag \textit{et al.} (1991)\textsuperscript{34} bonded ceramic brackets with 3 different filler concentrations (30\%, 55\% and 80\%) and found that the 80\% filler had significantly greater bond strength than the 30\% and 55\% filler content. They also commented that the lower filled resins had more bracket drift, which may result in reduced accuracy of placement and so the increased viscosity of the highly filled resin may also improve accuracy of bonding.

It is possible that not only the amount of filler but also the size of the filler particles may have an effect on bond strength. Schulz \textit{et al.} (1985)\textsuperscript{35} bonded metal brackets
with three Bis-GMA based resins and found that after 30 minutes the Concise (3M Unitek), a highly filled resin (80% filler), had the highest bond strength with Endur (28% filler) the least. The size of the filler affected the initial bond strength with the smaller filler size having the lowest bond strength at 30 minutes. However, they cautioned that this hypothesis required further study. After 48 hours there was no difference in bond strength (shear and tensile) suggesting that all of the resins, regardless of filler content, have sufficient properties to justify their use.

(2) Cements

Initially, orthodontic bands were attached to teeth with screw clamps but in 1871 Magill revolutionised their attachment with the introduction of an oxychlorid of zinc phosphate (zinc phosphate cement). Orthodontic bands were then attached to teeth with zinc phosphate cement, which was the reaction of zinc oxide and a phosphoric acid solution. This zinc phosphate cement, when set, is dimensionally stable and has good physical properties including low solubility in oral fluids. However, it does not bond to enamel and metals and therefore, could not be used to attach brackets directly to the teeth. Brackets and tubes were welded to the bands and then attached via the zinc phosphate cement, acting as a luting agent.

Polycarboxylate cement was the first chemically adhesive dental cement and was developed by Smith in 1968\(^{36}\). It is formed by the reaction of zinc oxide and
polycarboxylic acid solution. The polycarboxyl groups spaced along the polycarboxylic acid chain can chelate to calcium in enamel and dentine, resulting in a chemical bond between the tooth and the cement. Despite polycarboxylate cement having a chemical bond to dental and orthodontic substrates, it has a high solubility and a relatively low fracture resistance and can therefore not be used for direct bonding orthodontic attachments\(^1\).

Glass ionomer cement (GIC) was first reported in 1972\(^{37}\) and was described as a compound that contained a mixture of aluminosilicate glass powders and polymers of polycrylic acid. GICs are used in a wide range of clinical applications including restorations, pit and fissure sealants, cavity liners, luting cements for inlays, crowns and orthodontic bands and direct orthodontic bracket placement. GIC's have the advantage of fluoride release, antimicrobial activity, and adhesion to both enamel and metal; however, they are prone to early moisture contamination and take 24 hours to reach their maximum strength. Primarily, GIC has been used to attach orthodontic bands where it has been found to be superior to zinc phosphate cements\(^{38}\). Although GIC has been used to attach orthodontic brackets\(^{39,40}\) it is generally regarded to lack the necessary properties to retain the bracket through treatment\(^{41}\).

(3) Hybrids (Resin modified glass ionomer cements (RMGIC))

The incorporation of resin into glass ionomer cements to create “hybrid” cements has
allowed a snap set, which decreases moisture contamination and increases the rate of strength development\textsuperscript{42}. The amount of glass ionomer and resin varies and resulted in McCabe (1998)\textsuperscript{43} dividing these cements into 3 categories:

(a) Modified composites set through a polymerisation mechanism but contain ion-leachable glasses in an attempt to achieve fluoride release.

(b) Resin-modified glass ionomers, which set through an acid-base reaction, with or without polymerisation, contain components present in both composites and glass ionomers.

(c) Compomers, which set through a polymerisation reaction, but a limited acid-base reaction is also possible. Compomers are usually supplied as a single paste and contain all the major ingredients of both glass ionomers and resin composites, except water.

Cook\textsuperscript{44} bonded orthodontic brackets with a conventional GIC (Ketac, 3M Unitek) and found that the bond strength was less than a resin composite and the failure rate was 12\%, which is not clinically acceptable. He demonstrated that acid etching was not necessary but cotton rolls were needed to isolate the teeth. Other studies using different enamel pre-treatments and conventional GIC’s have also shown a high failure rate. Norevall \textit{et al.}\textsuperscript{45} found a failure rate of 36\% after etching with 37\% phosphoric acid bonding with Aquacem (3M Unitek). Miller \textit{et al.}\textsuperscript{46} had a failure rate of 33\% after preparing the enamel with polyacrylic acid and bonding with Ketacfil
(3M Unitek) and Oliveira et al.\textsuperscript{40} had a failure rate of 15.7% using a conventional GIC and not preparing the enamel surface. This suggests that conventional GIC’s perform differently and are affected by the enamel pretreatments.

\textit{In vitro} studies\textsuperscript{47,48} have demonstrated that light cured GIC achieves a clinically acceptable bond strength after 1 hour whereas the chemically cured GIC does not achieve that level until after 24 hours. Komori and Ishikawa\textsuperscript{49} demonstrated that Fuji Ortho (GC Corp, Japan) had a clinically acceptable bond strength, even after thermocycling. Movahhed et al.\textsuperscript{50} compared the bond strength of a RMGIC (Fuji Ortho LC, GC Corp, Japan) with 10% polyacrylic acid and a resin composite (Transbond) after preparation with a self-etching primer. They found that the RMGIC had clinically acceptable bond strength at 5 minutes (6.6MPa) and was even stronger at 15 minutes (9.6MPa). In contrast Bishara et al.\textsuperscript{51} found after 30 minutes the bond strength of Fuji Ortho LC was not clinically acceptable (0.4MPa). This may be due to differences in technique when preparing the tooth surface because if in the latter study the enamel was dry then the bond strength would be less.

Fricker\textsuperscript{52} compared the failure rate of a light cured conventional GIC (Fuji I, GC Corp, Japan) with a resin adhesive (System 1, ORMCO) in a clinical study. He found that over a 12-month period the GIC had a failure rate of 20% compared to 5% for the resin adhesive. The same author in 1994\textsuperscript{53} found that after preparing the enamel with a dentine conditioner and using a light-cured RMGIC (Fuji II, GC Corp, Japan) the failure rate was similar to composite cement. A similar study bonding only the anterior teeth with a light cured RMGIC and ensuring there were no occlusal
interferences found the failure rate to be 5%\textsuperscript{54}.

Silverman \textit{et al.}\textsuperscript{55} demonstrated that a light-cure RMGIC (Fuji Ortho LC) could be bonded successfully without etching and in the presence of saliva. This was confirmed by Jobalia \textit{et al.}\textsuperscript{56} who concluded that GIC approached the bond strength of resin adhesives and required the presence of moisture for optimal performance. Cacciafesta \textit{et al.}\textsuperscript{57} investigated the effect of saliva and water contamination on the bond strength of Fuji Ortho LC and found that for metal brackets the highest bond strength was found when the enamel surface was prepared with polycrylic acid and then contaminated with saliva (23.8MPa) and for ceramic brackets after polycrylic acid if water contaminated the surface (25.4 MPa). Acceptable bond strengths were achieved on unconditioned enamel in a dry field (12.0MPa) and unconditioned and wet enamel (9.0MPa). In contrast Chung \textit{et al.}\textsuperscript{58} found the bond strength of Fuji Ortho LC to be unacceptable on non-etched/dry and non-etched/wet enamel (2.96MPa and 2.11MPa) and etched/wet enamel (5.31 MPa). Cacciafesta \textit{et al.}\textsuperscript{59,60} clinically demonstrated that water contamination results in a 7.9% failure rate, salivary contamination a 5.1% failure rate but bonding on dry enamel gave a 34.5% failure rate. This may demonstrate that the technique of bonding with RMGIC’s may be technique sensitive and can be affected by other factors such as the type of bracket or the testing conditions.

Preparation of the tooth surface may affect the bond strength. However, pumicing prior to bonding with Fuji II and performing no enamel conditioning makes no difference to clinical failure rates\textsuperscript{61}. Some studies using different types and
concentrations of enamel conditioner have shown this can affect the bond strength of RMGIC's. These studies have shown that 20% polyacrylic acid performs better than 10% polyacrylic acid with 37% phosphoric acid etching increasing the bond strength further. Flores et al. and Toledano et al. have also demonstrated that etching with 37% phosphoric acid produced significantly higher bond strength with Fuji Ortho LC compared to non-etching with the non-etched values being clinically unacceptable in the latter study. Similarly Valente et al. found lower values for bond strength when bonding Fuji Ortho LC without etching. They concluded that it was necessary to prepare the enamel surface with either 10% or 37% phosphoric acid or 10% polyacrylic acid in order to achieve clinically acceptable bond strengths. Pithon et al. demonstrated that enamel that is not conditioned had unacceptable bond strength for Fuji Ortho LC and Ortho Glass LC. Conditioning with 37% phosphoric acid, 10% polyacrylic acid or a self-etching primer produced acceptable bond strength for Fuji Ortho LC, but Ortho Glass LC had unacceptable bond strengths. This demonstrates that the adhesive itself as well as the enamel preparation can affect the final bond strength.

Overall, in vivo studies have shown a wide variation in failure rates ranging from 3.2% to 34.5%. However, most studies are not directly comparable due to differences in design. Choo et al. found that after 12 months the failure rate of Fuji Ortho LC was 5.5% compared to 5.9% for multicure glass ionomer band cement and 7.2% for Transbond. The teeth were acid etched and left moist for the band cement and conditioned with polyacrylic acid and left moist for the RMGIC. Hitmi et al.
compared two operators bonding with Fuji Ortho LC and found that they had clinical failure rates of 8.2% and 5.9% (overall 7%), which was not statistically significant. The failure rate was greater for patients less than 12 (10.5%) and least for patients aged more than 20 (5.3%). They concluded that the good survival rate was due to enamel pre-treatment with polyacrylic acid and ensuring the bracket bonding was free from saliva. Hegarty and MacFarlane\textsuperscript{70} in a 12 month clinical trial found the failure rate of a RMGI was 10% compared to 4% for a resin composite over the same period. They found that when there was contact from the opposing occlusion the failure rate was four times higher for both adhesives.

Summers \textit{et al.}\textsuperscript{71} in an \textit{in vitro} and \textit{in vivo} study demonstrated that Fuji Ortho LC had a lower bond strength at 30 minutes and 24 hours than Light Bond but the bond strength would be clinically acceptable. Both materials increased in bond strength from 30 minutes to 24 hours. The clinical failure rates, over 1.3 years, were 6.5% for the Fuji Ortho LC and 5% for the Light Bond.

Rock and Abdullah\textsuperscript{72} compared the bond strength of a compomer (Dyract, Dentsply) with a composite resin adhesive using foil mesh and undercut stainless steel brackets. They found that clinically acceptable bond strengths were achieved after 15 minutes and 24 hours although they were lower than the resin composite. The foil mesh brackets had greater bond strength (12.12MPa) than the undercut retained brackets (7.28MPa) and increasing the curing time from 30 seconds to 60 seconds increased the bond strength at 15 minutes and 24 hours.
Millett et al.\textsuperscript{73} compared the shear debonding forces of a conventional GIC (Ketac-Cem), a compomer (Dyract), a RMGIC (Fuji Ortho LC) and two resin composite adhesives and simulated their survival rate by placing them in a ball mill. They found that brackets bonded with the conventional GIC had significantly lower bond strength and an increased failure rate. The bond strengths were comparable for the other materials.

Millett et al.\textsuperscript{74} compared the bracket failure rate and cariostatic potential of a compomer (Dyract) to a composite resin (Right On, Reliance). They found that the failure rates were comparable, 17\% for the compomer and 20\% for the composite resin, with less demineralisation associated with the compomer.

Rix et al.\textsuperscript{75} compared three orthodontic adhesives, a RMGIC (Fuji Ortho LC), a compomer (Assure) and a composite resin control (Transbond XT). They found that although the composite resin had higher bond strength (20.19MPa) the RMGIC (13.57MPa) and the compomer (dry 10.74MPa, wet 10.99MPa) had clinically acceptable bond strengths.

Whilst conventional GIC’s did not have acceptable bond strength it has been shown that the RMGIC’s can have acceptable bond strength provided the enamel surface is conditioned.
(B) Thickness of adhesive used

The thickness of the adhesive layer under a bracket may be important for both final tooth position and bond strength. The pre-adjusted appliances compensate for the differing thickness of teeth and it is necessary for an even layer of adhesive to be applied under each bracket to allow it to take full advantage of the prescription and to avoid or reduce the number of compensatory bends to be placed in the arch wire. It has been reported that a minimal thickness of adhesive is ideal for optimal bond strength with an increased thickness weakening the joint due to the introduction of imperfections and increased polymer shrinkage. According to the beam theory, the further the applied force is from the bonding surface, the higher the applied moment and therefore, the increased chance of bond failure. Pender et al. indicated that molar brackets that had less anatomical detail and therefore more adhesive between the bracket and the tooth failed at lower bond strengths. Schechter et al. compared the shear and tensile bond strengths of two chemically cured composite resins and their thickness. The tensile bond strength was unaffected by increasing the adhesive thickness whereas the shear bond strength decreased. However, Evans and Powers compared chemically cured and no-mix composite resins and found that the tensile bond strength decreased with increased adhesive thickness. This was similar to Jost-Brinkmann et al. who reported similar results for no-mix composite resins. They found that the thickness of the adhesive did not affect the tensile bond strength of chemically cured composites. It also suggested that light cured adhesive achieved
maximum bond strength at 0.2 millimetres and was significantly weaker at 0 millimetres. This was different to Mackay\textsuperscript{76} who found that for two chemically-cured and two light-cured composite resins, increasing thickness of the adhesive from 0 to 0.26 millimetres had no statistically significant effect although there was a trend towards a reduced bond strength. Arici \textit{et al.}\textsuperscript{83} investigated the effect of varying the thickness of a light cured, resin modified glass ionomer cement compared to a light cured composite resin control at 0, 0.25 and 0.5 millimetre thicknesses. The composite resin showed higher bond strength for all thicknesses. However, the composite increased in shear bond strength but decreased in tensile bond strength from 0 to 0.5 millimetres. The tensile and shear bond strength of the glass ionomer increased from 0 to 0.25 millimetres and decreased from 0.25 to 0.5 millimetres.

Although not conclusive, these studies demonstrate that there can be a difference in tensile and shear bond strength by varying the thickness of the adhesive and therefore the thickness should be standardised for bond strength testing.

To simplify the bonding process and reduce the number of bonding variables pre-coated brackets were introduced in 1991. The amount of adhesive is standardised, which may have several advantages: consistent quality and quantity of adhesive, reduced waste during bonding with easier clean up following debonding, reduced risk of contamination of the base, reduced chair time, better inventory control and improved bond strength and reduced clinical failure\textsuperscript{84,85}. The adhesive pre-coated brackets (APC) contain a dual cure Transbond adhesive with a greater amount of
filler (80%) than Transbond XT (77%) with the amount of Bis-GMA and Bis-EMA reduced by 2% and 1% respectively. 

In Vitro studies are contradictory in terms of bond strength with Bishara et al. demonstrated that ceramic APC brackets had a similar bond strength (12.7MPa) to ceramic brackets bonded with Transbond XT (10.4 MPa) whereas metal APC brackets bond strength was reduced (5.4 MPa cf 7.2 MPa). The metal APC brackets had a greater frequency of bond failure between the bracket and adhesive, which suggests that the increased filler content may not penetrate the mesh as efficiently. In contrast Sunna and Rock found that APC brackets had a similar bond strength provided they were cured for 40 seconds. If the cure was 10 or 20 seconds the APC brackets demonstrated significantly reduced bond strength. The same authors in a randomised clinical trial with a six month observation period found that there was no significant difference in the failure rate of the APC brackets (9.8%) compared to non-coated brackets.

Kula et al. in a split mouth design compared clinical failure rates of APC brackets with non-coated brackets bonded with Transbond XT. They found that there was no difference in failure rates over the 12-month observation period (8.2% cf 6.9%). Similar results have been found in a 6 month randomised clinical trial with metal brackets (APC 8.06% cf non APC 7.37%) and over the entire treatment with Clarity ceramic brackets (3M Unitek), where there was no bracket failure in either group.

The bond strength of APC metal brackets and self-etching primer (SEP) has been shown to be adequate for clinical use by Cacciafesta et al. and Hirani and Sherriff. Bishara et al. compared the bond strength of metal and ceramic APC brackets
bonded with a SEP and found that they both had clinically acceptable bond strength. Standardising the amount of adhesive, by providing the bracket as a pre-coat (metal or ceramic), does not have an advantage in bond strength or in terms of clinical failure.

(C) Preparation of the tooth surface

The advent of the acid etch technique by Buonocore\textsuperscript{30}, followed by the first direct bonded attachments in the 1960's by Newman\textsuperscript{26,27}, Mitchell\textsuperscript{29,94} and Cuerto\textsuperscript{28}, rapidly modified the way in which orthodontics was practiced. The bond strength achieved can be influenced by the type and concentration of the acid, the duration of etching, not applying etch, sandblasting the tooth surface, laser etching, applying moisture insensitive primers, self-etching primers, crystal growth and bonding to other surfaces such as amalgam, alloys, composite and ceramics.

Type and concentration of the acid

Buonocore originally used phosphoric acid at a concentration of 85\% for 30 seconds to improve the bond strength of acrylic restorative resins. Etching enamel with phosphoric acid provides micromechanical retention by a variety of means, ranging from preferential dissolution of the prism cores resulting in a honeycomb appearance to preferential dissolution of the prism peripheries resulting in a cobblestone appearance\textsuperscript{95}. Silverstone \textit{et al.}\textsuperscript{.96} evaluated the effects of acid concentrations from 20-
70% over time periods of 1 –5 minutes. They observed three basic etching patterns: Type 1, dissolution of prism cores; type 2, dissolution of prism peripheries; and type 3, a mixture of types 1 and 2. Galil and Wright\textsuperscript{97} used five different acid concentrations from 30-50% applied for 70 or 90 seconds and reported and added two additional patterns: type 4, pitted enamel surface and type 5 flat smooth surface. Barkmeier \textit{et al.}\textsuperscript{98} reported that the shear bond strengths obtained after etching with a 5% acid were comparable with those obtained with a 37% acid gel. Legler \textit{et al.}\textsuperscript{99} found that 5%, 15% and 37% phosphoric acid concentrations produced equivalent shear bond strengths. Carstensen\textsuperscript{95} evaluated the effects of phosphoric acid at 2%, 5%, 10%, 20% and 40% applied for 60 seconds. He confirmed the presence of the five different etching patterns but also observed that in general type 1 and type 2 dominated at concentrations between 20% and 40%. The same author\textsuperscript{11} compared the application of 2% and 37% acid etch for 30 seconds on anterior teeth. The clinical study found that the 2% etch was sufficient with the only difference being the amount of adhesive left on the tooth, which was greater in the 37% etch group. Orthodontic brackets bonded to extracted premolars and etched with either a 2%, 5% or 37% acid concentration were tested in shear and although the 2% etch had a statistically reduced bond strength, it would be clinically acceptable\textsuperscript{100}.

Bhad and Hazarey\textsuperscript{101} studied the etch pattern and compared the shear bond strength after etching with 5% and 37% phosphoric acid. They found that there was less mineral loss with the 5% etch and no difference in bond strength. This suggests that a 5% phosphoric acid etch for 60 seconds is an alternative for successful clinical
bonding of orthodontic brackets.

Sadowsky et al.\textsuperscript{16} in an \textit{in vivo} study compared 15\% and 37\% phosphoric acid etching for 60 seconds and found that there was no significant difference in the failure rate (6.63\% cf 3.06\%).

Although some studies have demonstrated that a lower etch concentration can have acceptable bond strength and potentially a better bond failure pattern reducing clean up a 37\% concentration continues to be used. This may be due to the findings of Chow and Brown\textsuperscript{102} who demonstrated that the application of solutions of phosphoric acid greater than 27\% resulted in the formation of monocalcium phosphate monohydrate (MCPM), while the main product of weaker phosphoric acid solutions is dicalcium phosphate dihydrate (DCPD). MCPM is more soluble than DCPD and will be more readily washed from the enamel after etching.

To try to minimise the amount of enamel lost and increase the resistance to demineralisation around orthodontic brackets, alternative enamel preparations have been tried. These include weaker acids such as maleic acid, nitric acid, citric acid and polyacrylic acid. Different combinations of conditioning agents have been used for the glass ionomer cements to increase their bond strength to be comparable with the resin composites as they then have the advantage of fluoride release.

Gardner and Hobson\textsuperscript{103} etched extracted premolars for 15, 30 and 60 seconds with 37\% phosphoric acid and 2.5\% nitric acid. They found that as the time increased the quality of the etch increased. However at all three time frames the phosphoric acid
was more effective at producing a good quality etch. Urabe et al.\textsuperscript{104} compared the shear bond strengths of metal, ceramic and plastic brackets bonded with different concentrations of maleic and phosphoric acid gels and solutions. They found that there was no difference between 2\%, 10\% and 37\% phosphoric acid and 10\% maleic acid for each bracket type.

Fajen et al.\textsuperscript{105} compared 3 glass ionomer cements after preparing the tooth with pumice, pumice and 45\% polyacrylic acid and pumice and 1.23\% acidulated phosphate gel (APF). They found that there was a large variation in bond strength between the three glass ionomers used with the application of polyacrylic acid or APF gel not significantly affecting the bond strength. Yamamoto et al. compared no preparation, 10\%, 20\% polyacrylic acid, 12\% citric acid and 35\% phosphoric acid application prior to bonding glass ionomer cement. They found that all of the tooth conditioning agents improved bond strength with 20\% polyacrylic acid having good bond strength and a relatively small amount of enamel erosion. Bishara et al.\textsuperscript{62} compared preparing the enamel surface with 10\%, 20\% polyacrylic acid and 37\% phosphoric acid and bonding orthodontic brackets with a resin-modified glass ionomer cement. They found that etching with 37\% phosphoric acid significantly increases the bond strength in the first 30 minutes (6.1MPa) compared to the 10\% and 20\% polyacrylic acid (0.4 and 3.3MPa).

Garcia-Godoy et al.\textsuperscript{106} compared 38\% phosphoric acid etching for 60 seconds with a 60\% phosphoric acid gel containing 0.5\% sodium fluoride with the latter having a significantly higher bond strength, however the higher acid concentration may have
accounted for why the addition of the fluoride did not reduce the bond strength.

Bishara et al.\textsuperscript{107} compared the bond strength of orthodontic brackets bonded with 10% maleic acid, 37% phosphoric acid and an acidic primer. They found that all provided an acceptable bond with a highly filled (77%) resin adhesive, but with the acidic primer with a lightly filled (10%) resin adhesive the bond strength was significantly lower, albeit clinically acceptable. However it demonstrated that acidic primers can successfully bond to enamel in 1 step (see Self etching Primers).

Kim et al.\textsuperscript{108} used various combinations of APF gel incorporated into 37% phosphoric acid etch in an attempt to reduce the amount of enamel lost on etching. They found that as the concentration of the APF increased the bond strength decreased. They recommended that a mixture of phosphoric acid and APF gel (50% and 66% APF fraction) can be used as an etchant substitute without loss of bond strength.

The duration of the etching

The time required for proper bonding of orthodontic brackets has been investigated. Brannstrom and Nordenvall (1977)\textsuperscript{109} compared the effects of etching with 37% phosphoric acid for 15 and 120 seconds and found that there was no appreciable differences in the appearance of the enamel. Nordenvall \textit{et al.} (1980)\textsuperscript{110} compared the effects of etching for 15 or 60 seconds with a 37% phosphoric acid solution. They found that there was no difference for deciduous teeth; young permanent teeth etched
for 15 seconds produced more retentive conditions than those etched for 60 seconds; and for old permanent teeth the 60 second etch was more effective. Brannstrom et al. (1982)\textsuperscript{111} confirmed the results when etching young permanent teeth with a 37% phosphoric acid gel or liquid for 15 and 60 seconds. Other studies\textsuperscript{112,113} have also demonstrated acceptable bond strengths with a 15 second etch time. Wang and Lu (1991)\textsuperscript{114} compared the tensile bond strengths of orthodontic brackets after etching times between 15 and 120 seconds. They found no difference in bond strength for 15, 30, 60 or 90 second etch times and a significantly lower bond strength with the 120-second etch. The enamel fragments were increased whenever etching was over 30 seconds. They proposed that the optimal etching time would be 15 seconds.

Gardner and Hobson\textsuperscript{103}, using premolars, found that quantity of good etch pattern was time specific with 15 seconds being significantly less effective than 30 or 60 seconds. However, there was no advantage to etching for 60 seconds over 30 and therefore they concluded that premolars should be etched for 30 seconds. They also commented that as premolar teeth etch less well than anterior teeth it may be possible to etch anterior teeth in less time.

A clinical study by Carstensen\textsuperscript{115} compared the failure rates of brackets after etching for 15-20 seconds and 30-35 seconds. They concluded that after 9 months the shorter etch was as effective as the longer with only 2 brackets lost (both from the shorter etch group). Kinch et al.\textsuperscript{116} compared the bond failure rate and type of adhesive failure after etching for 15 and 60 seconds and found that there was no difference between the groups but there were differences in bond failure site relating to the
position in the dental arch, with posterior teeth having a higher failure rate than anterior teeth. They suggest that 15 seconds etch time is adequate for clinical use. In summary, 15 seconds of etching with 37% phosphoric acid is recommended for preparation of the enamel for bonding with composite resin adhesive, it gives good bond strength and minimises the loss of enamel from the tooth surface.

No surface preparation

If orthodontic brackets could be bonded without preparation of the tooth surface it would mean that no enamel would be lost, leaving the outer layer, which is the most resistant to caries attack intact. It would also simplify the bonding procedure making it more efficient.

Composite resin adhesives require etching of the tooth surface to have adequate bond strength and therefore it is glass ionomer cements that have been tested without the application of a conditioning agent.

Wiltshire\textsuperscript{117} bonded buttons to extracted premolars with a glass ionomer cement with and without etching with 37% phosphoric acid. He found that there was no difference in the bond strength and that less cement was left on the tooth when the surface was not etched. Jobalia \textit{et al.}\textsuperscript{56} bonded orthodontic brackets under six different enamel surface conditions (dry non-etched, moist etched, moist non-etched, moist non-etched rebounded, moistened with a salivary substitute, moistened with human saliva). They found that the light cured glass ionomer cement approached the strength observed for
resin adhesives and required the presence of moisture on the enamel surface for optimal performance. In contrast, Meehan et al.\textsuperscript{118} found that a resin modified glass ionomer (Fuji LC) had a weaker, unacceptable bond strength when used without a conditioner and on a moist surface. This was in agreement with Oliviera et al.\textsuperscript{40} who, in a clinical study using a split mouth design, compared the bond failure rate of a resin modified glass ionomer cement (Fuji LC) without tooth conditioning and a composite resin adhesive (Concise, 3M Unitek). They found that bonding with the glass ionomer resulted in more first time bond failures (28.1\% cf 15.7\%) and that the use of heavy arch wires was largely responsible, because when light and medium wires were compared there was no difference. Cacciafesta et al.\textsuperscript{59,60} compared the clinical performance of a resin reinforced glass ionomer cement when bonded onto dry teeth and teeth soaked in saliva and water. They found that Fuji Ortho provided adequate bond strength when used on teeth soaked with water and saliva but not when used on completely dry teeth. Harari et al.\textsuperscript{119} used a multipurpose dental adhesive (IntegraCem, GC Corp, Japan) to bond orthodontic brackets (stainless steel and ceramic) to unetched enamel and found that adequate bond strength was achieved and there was no significant difference between the IntegraCem and Fuji Ortho LC.

It is possible to bond orthodontic brackets without etching or conditioning the tooth surface; however, the method may be technique sensitive.
Pumice

Buonocore’s original technique for bonding to enamel included a step to remove surface material from the tooth prior to acid etching. Since direct bonding of orthodontic brackets became popular in the 1970’s, pumice prophylaxis followed by enamel etching has been the recommended routine for achieving a strong enamel-resin bond. The first evidence for this was from Scanning Electron Microscope (SEM) studies showing that pumice prophylaxis removes organic material such as the acquired pellicle, which has been hypothesized to inhibit optimum etching from being achieved\textsuperscript{120}. From restorative dentistry research into pit and fissure sealants it has been shown that it is not necessary to pumice before application of the etch as the etch itself was adequate at removing the acquired pellicle. Donnan and Ball\textsuperscript{121} in a double blind clinical study found no difference in fissure sealant retention rates, over one year.

Lindauer \textit{et al.}\textsuperscript{120} in a laboratory study compared the shear bond strength of orthodontic brackets and in a clinical study, assessed the bracket retention rates after using 37% phosphoric acid for 30 seconds and either pumicing and non pumicing. They found that there were no significant differences in the bond strengths or bracket retention rates (pumice failure 6.6%, non-pumice failure 7.4% over 18 months). However clinically all the patients brushed their teeth prior to bonding, which may have removed the acquired pellicle. The SEM images demonstrated similar etch patterns but in the non-pumiced samples there were some areas of plaque and/or
Barry\textsuperscript{122}, in a prospective clinical study compared the retention rates of orthodontic brackets after etching for 15 and 60 seconds. He found the failure rate to be 3.4\% for pumiced teeth and 3.5\% for non-pumiced teeth and concluded that pumice prophylaxis can be safely omitted prior to bonding with 15 and 60 second etch times. Ireland and Sherriff\textsuperscript{61}, in a clinical study compared the effect of pumicing/non-pumicing before bonding with a diacrylate cement and a resin modified glass poly(alkenoate) cement. They found that there was no difference in clinical bond failure rates between the pumicing and non-pumicing groups for the diacrylate or the resin modified glass poly(alkenoate) cements.

**Sandblasting the tooth surface**

Sandblasting (air abrasion or micro-abrasion) is an additional proposed mechanism of enamel pre-treatment. This technique makes use of a high-speed stream of aluminium oxide particles (50/90\textmu m), propelled by air pressure. This technique has been used in orthodontics for the treating of fitting surfaces of orthodontic bands and brackets to increase their bond strength\textsuperscript{123} and to increase the retention and bond strength of orthodontic brackets to amalgam, gold and porcelain\textsuperscript{124-126}. In addition it significantly increases the bond strength of stainless steel lower lingual fixed retaining wires prior to bonding\textsuperscript{127}.

This technique roughens the enamel surface and it has been suggested that this could
make the direct bonding of orthodontic brackets possible without acid etching and reduce the amount of enamel lost. Reisner et al.\textsuperscript{128} observed that sandblasting did not appear to damage the enamel surface. Olsen et al.\textsuperscript{129} found that sandblasting with aluminium oxide resulted in irreversible loss of enamel, whereas acid etching shows intact organic components that allow the etched enamel surface to remineralise. However, when the air pressure and time of exposure were tested\textsuperscript{130} it was shown that at low pressure and with a short exposure time the enamel loss was less than that of etching with 37\% phosphoric acid. Moreover with higher pressure and longer exposure time the enamel loss was greater. Therefore, the amount of enamel loss is under the control of the operator. They also found that the bond strength was significantly reduced when used as a prebonding procedure for a composite and a resin modified glass ionomer cement. This is in agreement with Reisner et al.\textsuperscript{128} and Olsen et al.\textsuperscript{129} with the latter demonstrating that a 90\µm particle size gave a better bond strength (3.6MPa) than a 50\µm aluminium particle size (2.3MPa), with both not achieving an acceptable clinical bond strength.

Sargison et al.\textsuperscript{131} compared the bond strength of stainless steel orthodontic brackets after acid etching with 37\% phosphoric acid for 15 seconds of sandblasting with 50\µm alumina for 5 seconds on extracted premolar teeth. They found that etching provided significantly greater bond strength (almost double at 64.7N cf 27.4N) and that sandblasting resulted in failure exclusively at the enamel/cement interface whereas etching demonstrated a mixed mode of failure. Canay et al.\textsuperscript{132} compared
sandblasting with 50μm aluminium oxide alone and prior to etching to conventional
etching for 15 seconds and found that sandblasting followed by acid etching produced
significantly the highest bond strengths (89.31N) with sandblasting alone producing
the lowest bond strength (38.05N). Therefore sandblasting can not be recommended
as an enamel conditioner. Abu Alhaija and Al-Wahadni\textsuperscript{133} compared 50μm
aluminium oxide sandblasting with acid etching with 37% phosphoric acid for 15
seconds and found that that sandblasting alone does not provide an adequate bond
strength for clinical use.

In summary, sandblasting alone cannot be recommended as an alternative to acid
etching as it does not provide a clinically acceptable bond strength.

\textbf{Laser etching the tooth surface}

The first direct application of lasers was reported in the dental field in 1964, when
they were used to inhibit caries by increasing the resistance of enamel to
demineralisation\textsuperscript{134}. Since then laser treatment has found orthodontic application in
reducing enamel decalcification\textsuperscript{135}, etching the tooth surface prior to bonding\textsuperscript{136} and
laser debonding\textsuperscript{137}.

Laser treatment of dental hard tissues involves the conversion of light energy to
thermal energy, which induces changes within the enamel to a depth of 10-20μm
depending on the type of laser and the energy applied to the surface. This localised
melting and ablation of the enamel surface is, in effect, etching through continuous
vaporisation and micro-explosions due to vaporisation of the water trapped in the hydroxyapatite crystal\textsuperscript{134}. Laser etching modifies the calcium to phosphorous ratio, reduces the carbonate to phosphorous ratio and water and organic component contents and leads to the formation of more stable and less acid soluble compounds, thus reducing susceptibility to acid attack and caries\textsuperscript{138}. Ariyaratnam \textit{et al.}\textsuperscript{139} measured the surface roughness of enamel after phosphoric acid etching and laser treatment and compared the bond strength of two composite materials. They found that the laser could create a surface roughness of similar value as the acid etch but the pattern is different and the bond strength of the composite is reduced. They concluded that the laser could not be recommended as a viable alternative to the acid etch technique.

Von Fraunhofer and Orbell\textsuperscript{134} used a Neodymium-doped Yttrium Aluminium Garnet laser (Nd:YAG) at 4 different settings for 12 seconds to prepare the enamel for orthodontic bonding. They found that the bond strength increased with increased power and energy output with the results indicating that adequate bond strength could be achieved at a power setting above 1 W and 20Hz. However, it was concluded that the highest setting of 3W at 20Hz for 12 seconds was necessary as at the lower energy settings some of the brackets did not achieve the clinically acceptable minimum bond strength. Usumez \textit{et al.}\textsuperscript{138} tested the shear bond strength of stainless steel orthodontic brackets after etching with phosphoric acid and laser energy at 1W and 2W with a Erbium, Chromium doped Yttrium Scandium Gallium Garnet laser (Er,Cr:YSGG). They found that the mean shear bond strength of the brackets at 2W
(8.23MPa) was comparable to acid etching (7.11 MPa) but at 1W the mean bond strength was significantly reduced (5.64MPa). However there was a large range of bond strengths seen in the laser groups, which make the reliability and predictability of laser etching questionable. Obata et al.\textsuperscript{140} prepared the tooth surface with a normal and a super pulse CO\textsubscript{2} laser and found that it created lower shear bond strengths (6.9 and 9.7 MPa) compared to acid etching (15.3MPa). Lee et al.\textsuperscript{141} compared the bond strength of acid etching, laser ablation and combinations of acid etching and laser ablation. They found that laser ablation alone provided similar bond strength as acid etching (13.0 MPa cf 11.8 MPa). However combining acid etching and laser ablation (10.4 MPa) and laser ablation and acid etching (9.1 MPa) resulted in reduced bond strengths.

Overall, it is possible for laser etching (ablation) to produce a similar bond strength as acid etching but the predictability of that bond strength may be questionable and further research is required.

**Moisture Insensitive Primers (MIP)**

The majority of the current orthodontic bonding materials are composite resins based on the Bis-GMA formula\textsuperscript{15} (bis-phenol A glycidyl methacrylate). In order for composite resin adhesives to bond successfully, it is necessary to have a completely dry, isolated field\textsuperscript{142}. Occasionally, ideal isolation cannot be achieved as moisture control can be a problem in hard to reach areas, such as second molars, lower
premolars and partly erupted teeth. If etched enamel becomes wet, most of the porosities become plugged and resin penetration is impaired, this results in tags of insufficient length and the micromechanical retention is compromised\textsuperscript{143}. The detrimental effect of moisture on orthodontic bonding may also relate to water adsorption and exertion of a plasticising effect in the polymer network from the creation of hydrated zones at polar monomer sites and oxidation of pendant C=C bonds attached to the network which release by-products such as formaldehyde, so producing a plasticising effect\textsuperscript{144}. This has resulted in the introduction of orthodontic bonding systems that can perform in the presence of moisture. There are essentially two types of material:

(1) Materials that bond in the presence of moisture, essentially hydrophilic primers that were initially used for dentine bonding procedures. The primer contains 2-hydroxyethyl methacrylate, polyalkenoate co-polymers with carboxylate and ethanol\textsuperscript{31}.

(2) Materials that require the presence of moisture for proper polymerisation, i.e. Cyanoacrylate. The cyanoacrylates are available as a single paste or a powder/liquid and require no additional bonding agent. However, the surface must be intentionally wetted prior to their application. The setting reaction involves two steps. Firstly the isocyanate groups react with water, forming an unstable carbamic acid component, which rapidly decomposes to carbon dioxide and the corresponding amine. Then in
the second step the amine reacts with residual isocyanate groups, cross-linking the adhesive through the substituted urea groups. However, if there is excessive water only the first step of the reaction takes place, resulting in the formation of brittle polymer films. Another problem with these systems may be the release of carbon dioxide during the prolonged setting reaction, as it is only capable of limited diffusion through the adhesive film as polymerisation proceeds and may become trapped, forming voids or gaps with detrimental; effects on the interfacial strength. The manufacturers emphasise that contamination with saliva must be avoided, because this will disturb the setting process and adversely affect the structure and performance of the material\textsuperscript{145}.

Littlewood \textit{et al.}\textsuperscript{146} investigated the \textit{in vitro} bond strength of brackets bonded with a hydrophilic primer and compared it to conventional primer. The teeth were tested under dry conditions and they found that the hydrophilic primer had a lower bond strength than the conventional primer (6.43 MPa cf 8.71 MPa). Grandhi \textit{et al.} (2001)\textsuperscript{31} compared conventional primers and Transbond MIP in dry and wet (water and saliva) conditions. They found that the bond strength for the MIP was greater than that with the conventional primer and that a greater bond strength was achieved with Transbond XT light cured composite, compared to Concise self-cured composite adhesive. However, MIP is light cured and it was not light cured with the Concise, which may explain its lower bond strength. Schaneveldt and Foley\textsuperscript{147} compared the bond strength of Assure primer and resin, Transbond MIP with Transbond XT and
conventional etching with Transbond XT. A thin coat of saliva was applied before and after the Assure and MIP were placed. They found that the bond strength of conventional etching (15.82MPa) was higher than all the groups except the MIP, which was cured prior to saliva contamination (14.02MPa). All of the bond strengths were clinically acceptable. Light-curing the Transbond MIP and Assure before contamination has been shown to increase the bond strength as it is thought to ensure that there is resin tags of sufficient length and numbers before the saliva or blood blocks the pores. Rajagopal et al. compared the shear bond strength of orthodontic brackets bonded with Transbond MIP, a self etch primer and a conventional primer under dry and wet (saliva) conditions. They found that the MIP and self-etching primer had a clinically acceptable bond strength (9.07MPa, 10.79MPa) under wet conditions, whereas the conventional primer under wet conditions was inadequate (4.69MPa).

Littlewood et al. in a randomised clinical trial using a split mouth design compared the failure rates (over 6 months) of teeth bonded with a hydrophilic primer and a conventional primer. They found that there was an increased risk of failure with the hydrophilic primer (failure rate 18.8% cf 6.8%). Mavropoulos et al. compared the bonding with Transbond moisture insensitive primer and Unite (a chemical cured composite) and a fluoride releasing light cured moisture resistant compomer (Assure). They found that after 9 months the Transbond MIP had a lower bond failure rate (7.3%) than the Assure (13.8%) with premolars exhibiting a greater failure rate
than anterior teeth.

In conclusion, laboratory studies demonstrate that MIP can improve bond strength to wet enamel. The clinical studies are inconclusive with one suggesting a much greater failure rate and the other an acceptable failure rate. However, it is important when comparing the actual bond strength to consider the fact that some studies are performed on bovine enamel, which has been reported to have a lower bond strength (21-44%) than human enamel\textsuperscript{150}.

Howells and Jones\textsuperscript{151} tested a “pre-production” cyanoacrylate bonding system. They found that when the teeth were stored in saline the shear bond strength deteriorated and concluded that it would be unsuitable clinically. Al-Munajed \textit{et al.}\textsuperscript{152} compared the shear bond strength of SmartBond, a cyanoacrylate, with Right-on, a no mix chemically activated BIS-GMA composite adhesive after acid etching. They found that the bond strength of the SmartBond was inadequate after 24 hours and deteriorated further at 3 months. The hydrolytic instability of the material suggests it is unsuitable for clinical use. In contrast, Bishara \textit{et al.}\textsuperscript{153} found that after acid etching the cyanoacrylate (SmartBond) achieved a similar bond strength (5.2MPa) as conventional etching (5.8MPa). However, this study does not define the timeframe in which the samples were debonded and how the samples were stored. The same authors (2002)\textsuperscript{154} tested orthodontic brackets bonded to extracted molars with cyanoacrylate within 30 minutes of bonding and after 24 hours (stored in deionised water) and compared them to composite. They found that the shear bond strength at
30 minutes was comparable (5.8MPa cf 5.2MPa) and lower at 24 hours (7.1MPa cf 10.4MPa). Bishara et al.\textsuperscript{155} tested the bond strength of orthodontic brackets bonded with cyanoacrylate and thermocycled from 5-55°C 500 times. They found that the bond strength was clinically satisfactory at 24 hours (7.1MPa) but after thermocycling it had lost 80\% of its strength (1.5MPa). This suggests that it would be unacceptable clinically.

Karamouzos et al.\textsuperscript{156} in a clinical trial using a split mouth design bonded with SmartBond (Cyanoacrylate) in the presence of moisture and with System 1, which is a standard chemical cure composite resin. They found that the failure rate for the Smartbond was 22.4\% compared to the System 1, which was 5.1\%. The distribution of the failures was similar with more failures occurring in the premolar region. Le et al.\textsuperscript{157} compared the bond failure rate of cyanoacrylate with a conventional light cured composite resin and found that over a period of 12-14 months the cyanoacrylate had a failure rate of 55.6\% compared to 11.3\% with the composite resin. This is an unacceptable failure rate.

In conclusion, cyanoacrylate is not a suitable bonding material for routine clinical use.

MIP's have been modified to add antimicrobial agents to attempt to reduce the numbers of bacteria that colonise the area adjacent of the bracket and therefore reduce
the incidence of decalcification. Karaman et al. (2004)\textsuperscript{158} compared the bond strength of Transbond MIP with three different antimicrobial agents added (two chlorhexidine varnishes and a chlorhexidine mouthwash) with that of a conventional resin composite. They found that the Cervitec varnish had the highest bond strength of the antimicrobial additives (16.77 MPa), then the EC40 varnish (13.70 MPa) and chlorhexidine mouthwash the lowest (10.60 MPa). However, all of the bond strengths were clinically acceptable. The modification of the MIP affected the ARI with the chlorhexidine mouthwash and EC40 varnish having higher scores indicating the bond breaking between the enamel and the adhesive.

\textbf{Self Etching Primer (SEP)}

Direct bonding of orthodontic brackets requires that the teeth first be cleaned with a slurry of pumice (or an oil free paste), then rinsed and dried. The surface is then etched with a phosphoric acid solution and rinsed ensuring that none of the etch comes into contact with the gingivae. The tooth must then be dried and a primer is applied prior to the bracket adhesive placement.

The introduction of the self-etching primers simplified the whole process. Essentially a self-etching primer combines the etching and priming steps. The active ingredient is a methacrylated phosphoric ester. Phosphoric acid and a methacrylate group are combined into a molecule that etches and primes simultaneously with the primer.

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penetrating the entire depth of the etch, ensuring excellent mechanical interlock. As with normal acid etching the phosphate group of the methacrylated phosphate ester dissolves the calcium and removes it from the hydroxyapatite. However, rather than being rinsed away, the calcium forms a complex with the phosphate group and is incorporated into the network when the primer polymerises. In this manner, the acid is neutralised. It is necessary to agitate the primer to ensure that fresh primer is transported to the surface of the tooth. Three mechanisms act to stop the etching process:

- The acid groups attached to the monomer are neutralised in a similar manner as is the phosphoric acid, by forming a complex with the calcium from the hydroxyapatite.
- As the solvent is driven from the primer during the air burst step, the viscosity rises, slowing the transport of the acid groups to the enamel interface.
- As the primer is light cured and the primer monomers are polymerised, transport of the acid groups to the interface is stopped.

Bishara et al.\textsuperscript{159} compared tooth preparation with Clearfil Liner Bond (a SEP) with conventional etching. Brackets rebonded with Transbond XT and etched with 20% polyacrylic acid were compared with brackets bonded with Fuji Bond L.C. They found that the SEP produced the lowest bond strength (2.8MPa), which would not be clinically acceptable. Bishara et al.\textsuperscript{160} using a different brand SEP (Prompt L-pop)
found that it could provide a clinically acceptable bond strength (7.1MPa). Transbond Plus SEP was shown to provide a clinically effective bond strength after 15 seconds application (8.0MPa)\textsuperscript{161}.

Bishara \textit{et al.}\textsuperscript{162} assessed the effectiveness of a 3 SEP's (one experimental and one fluoride releasing SEP) using conventional etching as a control. They found that the experimental primer produced a bond strength equivalent to conventional etching (9.7 cf 10.4MPa) but the other 2 SEP's provided significantly lower bond strengths (7.1 and 5.1MPa). Aljubouri \textit{et al.}\textsuperscript{163} found that the bond strength of SEP was significantly less than a conventional etch (2.88MPa cf 3.71MPa). However their method for debonding used a ball mill, which employs diverse forces of varying magnitude with bond failure probably occurring through a process of slow crack propagation generated within the bonding material by the force of the impact and mechanical action of the ceramic spheres. In contrast, Buyukyilmaz \textit{et al.}\textsuperscript{164} demonstrated clinically acceptable bond strength for three SEP's (Transbond Plus 16.0 MPa, Clearfil SE bond 11.5 MPa and Etch and Prime 3.0 9.9 MPa). Larmour and Stirrups\textsuperscript{165} demonstrated acceptable bond strength for Transbond Plus (7.2MPa cf control 7.1MPa). However, when bonded to a wet enamel surface the bond strength was reduced (5.2MPa). Laboratory studies indicate that it is possible to produce acceptable bond strength with SEP but there is a great deal of variation. This may be due to operator error.

Grubisa \textit{et al.}\textsuperscript{166} bonded orthodontic brackets with SEP and compared three operators results. They found that there was variation with both acid etch and SEP bond
strengths depending on the operators. When bonding with the SEP the operator who followed the manufacturers instructions achieved a bond strength of 14.4MPa whereas the other two operators who either did not rub the SEP or apply a burst of air had bond strengths of 10.6MPa and 15.7MPa. Similarly, the three operators all used differing technique modifications for the acid etching resulting in bond strengths of 8.4, 13.6 and 18.6MPa. All of the bond strengths achieved were clinically acceptable but it highlights the fact that there is variation depending on how closely the instructions are followed.

The durability of the bond strength has been evaluated\textsuperscript{167} with brackets bonded with Superbond C and B after preparation of the tooth surface conventionally (65% phosphoric acid) and with Megabond SEP and then thermocycled. Although the phosphoric acid initially has a greater bond strength (20.4 cf 17.8MPa), after 2000 cycles the SEP has the greater bond strength (17.5 CF 10.4), which was maintained after 5000 cycles (15.3 cf 10.5).

Clinical evaluation of SEP was evaluated by Aljubouri \textit{et al.}\textsuperscript{13} who using a randomised clinical trial found that over 6 and 12 months there was no difference in the bond failure rate (12 months SEP 1.6%, Two stage 3.1%). This failure rate was low compared to other studies, which the authors reported may have been due to careful bonding technique following the manufacturer’s instructions and removing any occlusal interferences. Pandis and Eliades\textsuperscript{168} using Transbond Plus and One-Step self etching primer (Reliance) also demonstrated a low failure rate after 14 months (Transbond Plus 0.94%, One step 8.10%). In contrast Ireland \textit{et al.}\textsuperscript{169} found after 6
months that the failure rate for Transbond Plus was 10.99% compared to 4.95% with a conventional etch technique. Dos Santos et al.\textsuperscript{170} found that the 6 month failure rate of SEP was 10.6% compared to 7.4% for conventional adhesives. It is clear that there is a variability in the bond failure rates for the self-etching primer, which may be due to the operator. The adverse effect of water, saliva and blood contamination has been demonstrated \textit{in vitro}\textsuperscript{91,171,172} although some of the results are contradictory. Bishara et al.\textsuperscript{173} contaminated the tooth surface with saliva before, after and a combination of both times with the use of SEP and found that the saliva contamination before, after and in combination reduces the bond strength significantly (4.8, 4.8 and 1.7MPa cf control 6.0MPa). However, Campoy et al.\textsuperscript{172} in a similar study found that contamination after the application of the SEP had a lesser effect (11.61MPa) than if contamination occurred before (9.93MPa) or in combination (9.59MPa). Cacciafesta et al.\textsuperscript{91} using a conventional primer, a moisture insensitive primer and a SEP examined the effect of water and saliva contamination and found that non-contaminated surfaces had the highest bond strengths with all primers having clinically acceptable bond strengths. In most contaminated conditions, the SEP is the least influenced by contamination, except when water contaminates after its application when it is likely that a clinically unacceptable bond strength would be achieved. Oonsombat et al.\textsuperscript{171} examined the effect of blood contamination and found that if there is blood contamination before or after an acceptable bond strength will not be achieved (before 2.7MPa, after 1.1MPa, combination 0.5MPa). Therefore, if there is blood contamination at any stage it is essential to restart the bonding process.
A non-rinse conditioner (NRC) is similar to a SEP in that it prepares the enamel surface without the need for rinsing. However a primer still needs to be applied after the application of the NRC. Cehreli and Altay\textsuperscript{174} found that a NRC produced an aprismatic etch pattern (type 4 and 5), which was less destructive than an acid etch pattern but still potentially retentive. They indicated that the surface may be suitable for bonding with compomers. Bishara \textit{et al.} \textsuperscript{175} evaluated the bond strength of a NRC and a compomer (Dyract) and found that it produced a significantly lower bond strength than a conventional resin with acid etching (1.7 MPa cf 10.4MPa), which is not clinically acceptable.

Vicente \textit{et al.}\textsuperscript{176} compared the shear bond strength of a NRC and Transbond XT with a conventional etching and Transbond XT and found that there was no significant difference in the bond strength. The same authors\textsuperscript{177} used a SEP and a NRC and compared their bond strength to using a conventional acid etch and found that all of the bond strengths were equivalent (12.20MPa, 10.45MPa and 12.27 MPa) with the NRC producing a less aggressive etch pattern than the SEP and conventional etch and it also left significantly less adhesive than the SEP.

\textbf{Crystal Growth}

The crystal growth technique was introduced by Smith and Cartz\textsuperscript{178} and may have several advantages over acid etching\textsuperscript{179,180}. 

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- A minimal effect on the outer fluoride rich layer of enamel.
- The enamel surface is not significantly damaged during bonding or debonding.
- Few if any resin tags are left behind in enamel.
- Adequate bond strength for clinical practice is achieved.
- Debonding and clean up are easier with less chance of iatrogenic damage.
- The crystal interface offers the possibility of the incorporation of fluoride or other anti-plaque agents in the future to provide anticariogenic action.

The technique uses a polyacrylic acid with a residual sulphate ion to condition the teeth, forming crystals of calcium sulphate dihydrate or gypsum which are chemically bonded to enamel\textsuperscript{181}. The polyacrylic acid interacts with the enamel surface to produce ionised carboxyl groups. Strong ionic bonding between calcium ions at the enamel surface and the carboxyl groups provides crystal enucleation sites for the gypsum crystals, which in turn provide mechanical retention for the bonding resin. The polyacrylic acid produces only slight enamel etching with the acid concentration affecting the crystal structure and the ultimate bond strength\textsuperscript{182,183}

The bond strength of the crystal growth technique is dependent on the strength of the chemical bond between the enamel and gypsum crystals, with studies suggesting that bond failure occurs almost exclusively at this interface\textsuperscript{181,184}. The bond strength achieved with the crystal growth technique is between one-third and two-thirds of that achieved by conventional acid-etch technique\textsuperscript{183,185}. The bond failure rates of
brackets bonded with the crystal growth technique have been reported as 64.4 per cent compared to 3.4 per cent with conventional techniques\textsuperscript{185}.

Knox and Jones\textsuperscript{180} found that altering the lithium sulphate concentration of the crystal growth solution results in little change in the size, morphology and coverage of the crystal produced. However, the method does allow for reattachment of the bracket with no obvious deterioration in bond strength. The crystal growth shear bond strength was 73 N compared to 225.8 N for acid etch suggesting it is not a suitable alternative.

Jones \textit{et al.}\textsuperscript{185} in an \textit{ex vivo} study compared the crystal growth technique with conventional acid etch technique. The crystal growth technique produced significantly lower bond strengths for ceramic brackets in tensile loading (38.2 N vs. 54.4 N) and in shear loading (77.7 N vs. 162.2 N) and metal brackets in tensile loading (21.6 N vs. 58.9 N) and in shear loading (123.6 N vs. 211.2 N). The bond strengths for the crystal growth technique were below what would be considered clinically acceptable. However, the results were comparable to Jones and Pizaro\textsuperscript{187} who reported bond strengths of 132.4 N for crystal growth compared to 238.6 N with the acid etch technique.

Overall the reliability of the bond strengths demonstrated by the crystal growth technique are inadequate for clinical use.
Bonding to Amalgam

As orthodontic treatment becomes more acceptable for adult patients there are a greater number seeking treatment\textsuperscript{188}. Adult patients and sometimes adolescents may have amalgam restorations on the buccal surface of their posterior teeth, which can pose a problem if the orthodontist is planning to bond attachments to the teeth as the bond strength of conventional materials has proved inadequate. There are three basic types of silver amalgam used in restorative dentistry: (1) lathe cut, (2) spherical and (3) admixture (combination of lathe cut and spherical), with spherical amalgam alloy having a higher bond strength compared to lathe cut or admixed alloy when bonding with Panavia-EX\textsuperscript{189}.

There are a number of methods available to enhance bonding to amalgam. They include (1) modification of the metal surface by the use of intra-oral sandblasting or diamond bur roughening, (2) the use of intermediate resins that improve bond strengths (e.g. All-Bond 2, Enhance, Metal Primer) (3) new adhesive resins that bond chemically to non-precious and precious metals (e.g. 4-META resins, 10-MDP bis-GMA resins) and (4) and directly altering the alloy surface\textsuperscript{125,190-192}.

Intraoral sandblasting with the use of Concise has been shown to provide a bond strength of 5MPa (sd 1.3, range 3.4-6.4 MPa)\textsuperscript{125}, which coincides with the recommended minimum bond strength of 5-8 MPa\textsuperscript{20}, although this was less than half of the bond strength achieved with Concise and an etched enamel surface.
Metal bonding adhesives, such as Metal Primer, C and B Metabond and Amalgambond have been shown to improve the bond strength of composite resin to amalgam surfaces\textsuperscript{125,192,193}. It is thought that these adhesives bond to the oxidised surfaces of non-precious metals by forming a hydrogen bond between the 4-META molecule and the oxygen or hydroxyl groups in the metal layer\textsuperscript{191}. Metal Primer used on an amalgam surface prepared with 50$\mu$m sandblasting for 5 seconds has been shown to have a mean bond strength of 27.3 MPa (sd 5.80) when tested in shear\textsuperscript{191} and 9.8 MPa (sd 3.0) when tensile tested\textsuperscript{192}.

An intermediate resin, All Bond 2 has been shown to be a successful bonding agent to amalgam\textsuperscript{125,192}. An amalgam surface prepared with 50$\mu$m sandblasting for 5 seconds has been shown to have a mean bond strength of 28.0 MPa (sd 4.66) when tested in shear\textsuperscript{191} and 8.9 MPa (sd 1.7) when tensile tested\textsuperscript{192}.

A technique that involves altering the surface of dental precious metals with gallium (Ga) and tin (Sn) liquid (Adlloy) to improve bonding with dental adhesives has been tested\textsuperscript{190}. In contrast to ion coating or tin-plating, Adlloy surface modification is easy to use and designed for intra-oral use. The mean shear bond strength of the brackets bonded with C and B Metabond and Adlloy was 13.19 MPa (sd 3.06), which is comparable to metal brackets bonded with conventional orthodontic resins and acid etched surfaces. This increase in bond strength may be due to the thin layer of Ga and Sn providing a chemical bond between the C and B Metabond and the Adlloy treated amalgam. The Adlloy surface modification reduced the bond strength of Concise
composite resin to amalgam (Concise and Adlloy mean 4.15 MPa sd 1.09 vs. Concise alone mean 4.53 MPa sd 1.54). Although this is not statistically significant, it may be due to the Adlloy treated amalgam having a smoother surface with fewer retentive sites for physical bonding of the Concise resin.

Other bonding agents such as Alloybond and Fuji Ortho LC have been tested in shear after sandblasting for 5 seconds with 50μm particles and roughening with a diamond bur. The mean bond strengths were 21.0 MPa sd 4.47 (sandblasting and Fuji Ortho LC) and 13.8 MPa sd 3.18 (sandblasting and Alloybond) and 4.61 MPa sd 2.06 (diamond bur and Fuji Ortho LC) and 4.71 MPa sd 1.32 (diamond bur and Alloybond). This suggests that neither adhesive would be suitable for use after roughening with a diamond bur but would be acceptable after preparation with an intra-oral sandblaster.

**Bonding to Casting Alloys (e.g. Gold)**

Posterior teeth are sometimes restored with full cast crowns. These may be made from high-noble gold alloys, reduced gold alloys, silver palladium alloys, other palladium based alloys (nickel chromium, cobalt chromium) and titanium. Methods suggested to increase the bond strength are (1) roughening the surface (with a stone, or by sandblasting), (2) the use of intermediate resins that improve bond strengths (e.g. All-Bond 2, Enhance, Metal Primer) (3) new adhesive resins that bond chemically to non-precious and precious metals (e.g. 4-META resins, 10-MDP bis-
GMA resins) and (4) and directly altering the alloy surface (Adlloy or tin plating)\textsuperscript{124,194,195}

Wood \textit{et al.}\textsuperscript{194} bonded lower incisor brackets to gold crowns and compared smooth and roughened surfaces, a lightly filled resin and a highly filled resin and the use of porcelain primers. The porcelain primers failed to provide a significant increase in bond strength when bonding to gold. However roughening the gold surface and using highly filled resin gave a bond strength of 27.3 lbs sd 7.53 and this had a similar bond strength to acid etching enamel and the use of a lightly filled resin (mean 28.83 lbs sd 8.04). Buyukyilmaz \textit{et al.}\textsuperscript{196} found that sandblasting the gold surface produced significantly stronger bond strengths than roughening it with a bur. The 4-META bonding resin plus sandblasting provided a better bond strength (mean 14.1 MPa, sd 2.9) than sandblasting and Concise alone (mean 4.1, sd 0.5) and also provided a bond strength comparable to conventional etching of human teeth with the use of Concise (premolar teeth mean 16.6 MPa, sd 4.1). The use of the intermediate resin (All-Bond 2) plus sandblasting and the use of Concise provided an improved bond strength (mean 10.9 MPa, sd 2.3) than Concise alone. With the tin-plating the bond strength of the sandblasted gold alloy only increased marginally (mean 7.1 MPa, sd 1.2).

Nollie \textit{et al.}\textsuperscript{195} compared Adlloy surface treatment to sandblasting a type-IV gold alloy and found that Adlloy treated gold offered an improved bond strength (mean 6.86 MPa, sd 1.86) than sandblasting (mean 3.36 MPa, sd 1.76).
Bonding to Composite Resin

It is not uncommon to find teeth that have been restored with composite resin or resin composite laminate veneers. As composite resin ages there are less unreacted methacrylate groups remaining on the surface, which reduces the potential sites available for crosslinking with a new resin. The bond strength of new composite to older composite is substantially less than the cohesive strength of the material\textsuperscript{197} but if the old composite surface is roughened clinically acceptable bond strengths can be achieved. A bond strength of 60-85\% of the bond strength of etched enamel has been reported for bonding to resin laminate veneers. Newman \textit{et al.}\textsuperscript{198} bonded stainless steel brackets to a composite bar (Isosit) with and without a silane coupling agent. They found that after thermocycling, the silane application gave a slight increase in bond strength but both mean bond strengths were equivalent to the bond strength after acid etching enamel. Chunhacheevachaloke and Tyas\textsuperscript{199} reported mean shear/peel bond strengths in the range of 17.1 to 19.2 MPa for ceramic bracket bonded to composite resin. Lai \textit{et al.}\textsuperscript{200} compared the bond strength of metal, ceramic and polycarbonate brackets with light cured and chemical cured composite resins and a light cured resin modified glass ionomer cement with and without thermocycling. They found that the mean bond strengths were significantly different for all the groups with all demonstrated acceptable bond strength except for the polycarbonate bracket and the chemical cured composite after thermocycling.
One of the most widely used indirect bonding techniques today is a modification of the Thomas technique, whereby the brackets are placed on the plaster model and the composite resin is cured creating a custom base. The brackets are then bonded intra- orally with a thin layer of sealant creating a bond between the enamel and the preaged custom composite base. Research has shown that once a composite resin is contaminated, polished, aged or laboratory processed the bond strength of freshly added composite drops considerably. Shiue et al. tested the bond strength of metal and ceramic indirectly bonded brackets using the Thomas technique and ageing the composite for 7 days. They found that there was no difference in brackets placed directly or indirectly. Klocke et al. compared the bond strength of thermally, light and chemically cured custom bases in a modified Thomas indirect technique and found that after 7 days the bond strengths of the light cured base (14.99MPa) and chemical cured base (14.41MPa) were comparable to directly placed brackets (13.88MPa) but the thermally cured bases had a lower bond strength (7.28 and 7.07MPa). A similar study using chemically cured and light cured bases found that acceptable bond strength was found after up to 30 days. Polat et al. found that there were no differences in bond strength between a thermal cure (Reliance) and light cured (Transbond XT with Sondhi A and B) indirect bonding resins. The authors suggest that the difference in results to other studies may lie in the technique used. They used a single tray, similar to a clinical situation, whereas other studies used individual transfer jigs, which may have resulted in different thicknesses of adhesive. The in vivo aspect of this study demonstrated no difference in failure rate between the
two techniques over a 9-month period. Miles and Weyant\textsuperscript{205} in a split mouth design found that the failure rate for two chemically cured adhesives were 9.9% and 1.4% over a 6 month period.

Freudenthaler \textit{et al.}\textsuperscript{206} suggested that light cured fibre-reinforced composites (FRC) can be used in orthodontics for retention, anchorage and active tooth movement. They tested the bond strength of the FRC and brackets bonded to the FRC and found it to provide a clinically acceptable bond. It was weakest with the force directed 90° to the tooth surface.

Miwa \textit{et al.}\textsuperscript{207} suggested that bonding veneers prior to orthodontic bonding provided protection to the tooth surface. The glass ionomer cement veneers were placed on test premolars and brackets were bonded. They found that the bond strength to the veneers was comparable as those with the same cement to enamel.

\textbf{Bonding to Porcelain}

Porcelain restorations are especially common in adults where they are used in veneers, crowns and bridges. Porcelain poses a particular problem for the orthodontist as its surface is essentially inert and doesn’t bond readily to other surfaces. The reversible bonding of porcelain can be complicated by bond failure or porcelain surface damage upon debond. Therefore a number of methods have been attempted to
alter the surface characteristics of the porcelain to facilitate the bonding of orthodontic brackets. There are three categories of method that have been tried: (1) Mechanical, (2) Chemical or (3) A combination of mechanical and chemical.

Removing the glaze and roughening the surface to provide mechanical retention for the adhesive is achieved by sandblasting or air abrasion\textsuperscript{126,208-210}, diamond burs\textsuperscript{211}, a green stone\textsuperscript{212,213} or abrasive discs\textsuperscript{214}. Chemical alteration of the porcelain surface is achieved by either acid etching the surface to increase the mechanical retention of the adhesive or by changing the porcelain surface affinity to the adhesive materials. Hydrofluoric acid etches the porcelain surfaces and significantly increases the bond strength of orthodontic brackets\textsuperscript{210,215}. However, the porcelain loses its glaze and it can be difficult for the clinician to return it to its original lustre. Phosphoric acid\textsuperscript{209,210} and acidulated phosphate fluoride\textsuperscript{126,214} have also been used to etch the porcelain surface because they do not cause as much damage as hydrofluoric acid; however, they do not provide as strong a bond as etching with hydrofluoric acid. Changing the nature of the porcelain surface by using a silane-coupling agent has two effects. Firstly, it provides a chemical link between the dental porcelain and the resin and secondly, the organic portion of the molecule increases the wettability of the porcelain surface, thereby creating a more intimate micromechanical bond\textsuperscript{215}.

There are several factors that need to be considered when testing porcelains. Porcelains can be classified as feldspathic porcelains, aluminous porcelains and glass
ceramics\textsuperscript{126}. However, some studies use denture teeth\textsuperscript{194,198}, which have significantly different properties from the feldspathic porcelains commonly used in veneers, crowns and bridges. The chemical nature of dental porcelain at the surface has been shown to be modified in the presence of water such that samples that have been hydrated for 1 week will have a lower bond strength than samples that are not. Presumably, this is due to the hygroscopic nature of porcelain, specifically alkaline earth oxides contained within the porcelain (e.g., Al\textsubscript{2}O\textsubscript{3}). It is this alkaline layer of water at the porcelain surface that can interfere with the bonding mechanism\textsuperscript{215}.

Newman \textit{et al.}\textsuperscript{198} tested the shear strength of brackets bonded to porcelain with and without the use of a silane coupling agent and found that silane enhance the bond strength but the bond might not be adequate for clinical use, however denture teeth were used. Wood \textit{et al.}\textsuperscript{194} found that using primers on an intact glaze and after roughening the porcelain surface provided a satisfactory bond strength with roughening the surface prior to the primer application significantly increasing the bond strength. However, there was an increased risk of porcelain fracture during debonding. Smith \textit{et al.}\textsuperscript{216} found that application of a silane primer alone could provide a similar bond strength as roughening and application of a primer depending on the type of composite adhesive used. A heavily filled resin has been shown to produce a higher shear bond strength than a lightly filled resin\textsuperscript{211,217}. Nebbe and Stein\textsuperscript{218} also found that clinically acceptable bond strengths were obtainable on unglazed surfaces with the application of a porcelain primer.
Bourke and Rock\textsuperscript{209} compared the bond strength of metal brackets to feldspathic porcelain after glaze removal, application of hydrofluoric acid, phosphoric acid and silane priming. They found that thermally cycling reduced the bond strength significantly and that acceptable bond strength could be achieved with the use of a silane primer.

Zachrisson \textit{et al.}\textsuperscript{126} compared different combinations of sandblasting, silane coupling agents and acid etches and found that acceptable bond strength should be attained clinically after deglazing and either (1) etching with hydrofluoric acid, or (2) application of silane plus All Bond 2 primers A and B. Sandblasting and APF gel and sandblasting alone did not provide a satisfactory bond strength.

Other adhesive materials have been tested for suitability of bonding to porcelain, with Chung \textit{et al.}\textsuperscript{219} finding that etching with 9% hydrofluoric acid followed by application of silane significantly increases the bond strength of resin modified glass ionomer cement to porcelain. Larmour \textit{et al.}\textsuperscript{220} found that lower bond strengths were achieved when bonding to porcelain with a resin modified glass ionomer adhesive after etching with hydrofluoric acid than a conventional composite resin; however, the bond strength may be clinically acceptable. However, in both studies the samples were not thermally cycled, which may have reduced the bond strength further.

Zelos \textit{et al.}\textsuperscript{221} bonded two types of ceramic brackets on two types of porcelain with two different bonding systems and found that adequate bond strength was achieved using a silane primer on a glazed porcelain surface. This is in agreement with
Whitlock et al.\textsuperscript{222} who bonded porcelain premolar brackets with a two paste, no-mix and light cured adhesive to prepared porcelain and found that all provided adequate bond strength when a primer was used. Kocadereli et al.\textsuperscript{223} measured the tensile bond strength of porcelain orthodontic brackets after surface preparation with combinations of sandblasting, silane application and etching with 9.6% hydrofluoric acid. They found that etching followed by silane application provided the highest bond strength, followed by sandblasting and silane with sandblasting alone and etching alone being less effective. Huang and Kao\textsuperscript{213} found that composite brackets bonded to porcelain surfaces after etching with 9.6% hydrofluoric acid and priming with Scotchprime had the highest bond strength when they were not thermally-cycled, although they still had a clinically acceptable bond strength after thermal cycling.

A number of techniques have been shown to provide acceptable bond strength for brackets bonded to porcelain surfaces. It is important to warn the patient that there may be damage to the surface on debonding. Therefore, it may be better to preserve the glaze and use a phosphoric acid etch and silane coupling agent and then accept a slightly lower bond strength but reduce the chance of damage.

(D) Contamination of the tooth surface

Conventional resin composites require the use of an enamel conditioner, a primer and an adhesive resin to bond orthodontic brackets to enamel. Due to the hydrophobic
properties of these materials it is necessary to provide a completely dry and isolated field to obtain clinically acceptable bond strengths\textsuperscript{142}. When the etched enamel becomes wet, most of the pores become plugged, resin penetration is impaired, resulting in resin tags of insufficient number and length\textsuperscript{143}. Even a momentary saliva or blood contamination adversely affects the bond.

Hormati et al.\textsuperscript{224} found that etched enamel surfaces that were air dried after 60 seconds saliva exposure has significantly reduced bond strengths compared to teeth that were re-etched, rewashed and redried after similar saliva contamination. O’Brien et al.\textsuperscript{225} found that even after saliva contamination for 1 second, washing alone did not remove the oral fluid remnants and they recommended that the surface be re-etched.

The need for isolation is clear and Heringer et al.\textsuperscript{226} compared the bond strength of brackets bonded with cotton rolls and rubber dam isolation. They found that there was no difference in the bond strength of buccal or palatal brackets placed on premolars. The essence is to ensure good moisture control. However there are a variety of situations where maintenance of a dry field is impossible (for example around second molars, a surgically exposed tooth, a partly erupted tooth, poor gingival health).

Cacciafesta et al.\textsuperscript{91} assessed the effect of water and saliva contamination on the bond strength and bond failure site for 3 primers (Transbond XT, Transbond Moisture Insensitive Primer (MIP) and Transbond Plus Self Etching Primer(SEP)). They found that all performed equivalently with no contamination, with the SEP the least affected.
by water and saliva contamination except when the moistening occurred after the recommended 3-second air burst. Therefore, if bonding is delayed with a SEP and the enamel becomes moist after priming it is necessary to reprime the tooth surface. If bonding to a moist surface Transbond XT will not have an acceptable bond strength, whereas the MIP and SEP will, although it will be reduced compared to a non-contaminated surface. Campoy et al.\textsuperscript{172} assessed Adper Prompt L-Pop (3M ESPE) with saliva contamination at different stages. They found that bond strength was significantly reduced when saliva contamination occurred before and after priming and before priming. However they did not find as great a reduction in bond strength when saliva contamination occurred after priming. In all experimental groups the bond strength would have still been clinically acceptable. In contrast, Bishara et al.\textsuperscript{173} found that using a self-etch primer in the presence of saliva (contamination before, after and before and after primer use) resulted in significantly reduced bond strengths, such that they may not be acceptable clinically.

Oonsombat et al.\textsuperscript{171} measured the shear bond strength of orthodontic brackets bonded with a self-etch primer with blood contamination (before, after and before and after primer use). They found that blood contamination significantly reduces the bond strength whenever the contamination occurs to such an extent that the bond strengths would not have been clinically acceptable. Similar results were obtained by Cacciafesta et al.\textsuperscript{143} who tested a conventional primer (Transbond XT) and MIP (Transbond MIP) and although the MIP, after contamination, had significantly higher bond strength compared to the conventional primer it would have still been clinically
unacceptable. In contrast, Hobson et al.\textsuperscript{227} found that MIP provided clinically acceptable bond strength even after contamination with blood or moisture prior to the application of the MIP.

Sayinsu et al.\textsuperscript{148} investigated the theory that to reduce the negative effects of contamination on bond strength in problem areas, it would be advantageous to light cure the primer immediately after placement. They found that Transbond MIP and Assure had higher bond strengths if they were cured immediately before contamination occurred. Therefore, it is a possible technique to improve bond strength. Other methods may be to use a bonding agent that sets in the presence of moisture, such as glass ionomer cement or a cyanoacrylate. Reddy et al.\textsuperscript{228} compared the bonding of buttons with composite and resin-modified glass ionomer with contamination before and after bonding. They found that the composite resin had significantly greater shear bond strength, with both materials showing a decrease with contamination prior to bonding and little change with contamination after bonding.

Itoh et al.\textsuperscript{229} compared bond strengths of two light cured glass ionomer cements, with and without etching, at 5 minutes, 15 minutes and 24 hours and with water and saliva contamination. They found that at the shorter test times there were significant differences with water and saliva contamination having a reduced bond strength at 5 and 15 minutes for unetched enamel (water had a greater reduction). However, after 24 hours there were no significant differences between the two cements, indicating that glass ionomer cements may be useful in bonding in water or saliva contamination.
Cyanoacrylates require the presence of moisture to set and in general have been shown to have a lower bond strength\textsuperscript{152} or have an increased bracket failure over time\textsuperscript{157}. Although others\textsuperscript{153,154} have indicated that there is adequate bond strength there are no known investigations measuring the effectiveness of cyanoacrylates in saliva or blood contamination.

The quality of water passing through the waterlines is a potential contaminant for orthodontic bonding procedures. A number of antibacterial products have been recommended for reducing or eliminating the bacteria biofilm in the waterline. It is possible that the antibacterial agent used to disinfect the waterline may contaminate the tooth surface and reduce the bond strength. Bishara et al.\textsuperscript{230} found that the use of an iodide based disinfectant did not significantly affect the shear bond strength of orthodontic brackets bonded to human molars.

(E) Type of tooth

The most ideal tooth for bonding studies is the human maxillary central incisor as it has a nearly flat surface that is usually consistent from incisor to incisor without the concern of fitting a bracket base to a very curved surface\textsuperscript{150}. The improvement in oral health and improvements in restorative techniques has made it incredibly difficult to access human incisors for studies. Therefore, some studies\textsuperscript{231,232} have used human premolars, which are more readily available due to their removal for orthodontic purposes. However, they vary more in the curvature of their labial surface and this
adds the variable of the bracket base not closely fitting the tooth. Premolar testing results have been interpreted as being applicable to all teeth in the dental arches. This has not been proven and Hobson et al.\textsuperscript{233} examined whether premolar bond strengths are representative of the bond strength achieved on different teeth. Their findings suggest that there are significant differences between different tooth types and opposing dental arches. Upper anterior teeth demonstrated higher shear bond strengths than upper posterior teeth and lower posterior teeth demonstrated higher shear bond strengths than lower anterior teeth. This may be due to the fact that different teeth show a variation in their etch pattern after acid etching\textsuperscript{234,235}, which may affect the bond strength. This difference between teeth was confirmed by Linklater and Gordon\textsuperscript{236}. However, their pattern for bond strengths was different with upper and lower canines and premolars demonstrating higher bond strengths than incisors. They suggested that the differences may be due to the amount of apismatic enamel (premolars have greater proportions of apismatic enamel\textsuperscript{237}), the differing etch patterns or gross anatomical variability leading to inconsistent adhesive film thickness.

Areas of prismless enamel have been reported to occur more frequently in deciduous than permanent teeth\textsuperscript{238,239}. Prismless zones may negatively influence the retention of adhesives as it may be necessary to remove them mechanically or etch for a longer period. Due to wear and replacement of organic material by minerals during the maturation process the enamel surface of older teeth may have a different
composition to newly erupted teeth. Nordenvall \textit{et al.}\textsuperscript{110} assessed the etch patterns with a scanning electron microscope. They found that there was no difference in retentive conditions for deciduous teeth with etch times of 15 and 60 seconds, but for young permanent teeth, a 15 second etch time created more retentive conditions than a 60 seconds etch time. The reverse was true for old permanent teeth. Sheen \textit{et al.}\textsuperscript{240} assessed the bond strength after etching for 15 and 60 seconds and found that regardless of etching time the bond strength of older permanent teeth was greater than young permanent teeth. Knoll \textit{et al.}\textsuperscript{241} found \textit{in vitro} that incisors had a greater bond strength (mean 164.3 $\pm$ 35.1 kg/cm$^2$) than posterior teeth (mean 115.7 $\pm$ 41.1 kg/cm$^2$) and the difference probably lay in the bracket/resin interface.

This difference between teeth has been reflected clinically with a higher failure rate for posterior teeth. The failure rates have been reported as 5\% for anterior teeth and 15\% for posterior teeth. It is not known whether this reflects higher masticatory forces generated in the posterior of the mouth, the increased difficulty in maintaining a dry field or is due to the differences in enamel micromorphology. Incisal biting forces have been reported as 13-15kg\textsuperscript{242} and posterior biting forces 30kg\textsuperscript{19}.

Bovine lower incisors are readily available and an inexpensive substitute for human incisors. Bovine enamel is similar to human enamel and it has been shown that the enamel of all mammals appears to be similar on a histochemical and anatomical basis\textsuperscript{150}. However, some differences have been reported. Bovine enamel and dentine develop more rapidly during tooth formation leading to bovine enamel having larger
crystal grains and more lattice defects than human enamel, which may contribute to a lower critical surface tension. The difference in critical surface tension in bovine enamel compared to human enamel has been speculated to account for the slightly lower enamel bonding values seen with bovine teeth\textsuperscript{243}. Oesterle \textit{et al.}\textsuperscript{150} found that bovine incisors were shown to have enamel bond strength of 21-44\% weaker than human enamel with bovine deciduous teeth having a greater bond strength than bovine permanent incisors. However, bovine incisors that were used up to five times showed no statistically significant difference in bond strength, although the first bonding did have a slightly greater bond strength. Therefore, it could be an advantage of bovine incisors to reuse them multiple times without getting a significant decrease on adhesive strength.

\textbf{(F) Substrates chosen for bond testing}

The lack of standardisation of \textit{in vitro} studies makes the comparisons between studies difficult. As discussed previously different teeth are used (incisor and premolar) which can lead to topographical variation, which can affect the bond strengths demonstrated due to the fit of the bracket to the tooth surface or perhaps the differences in structure of the enamel. The bond strength can also be affected by the use of teeth from different species (human and bovine). In some studies the surface of the teeth is ground to attempt to standardise the topographical variants of the substrate and ensure the contact between the bracket and the tooth is more ideal\textsuperscript{244};
however, this adds the added variable of how the grinding took place and how much enamel was removed. This modification of the surface effectively exposes deeper enamel for bonding which potentially has different properties to the original surface layers, which have a higher fluoride content in the outermost 10μm\(^2\)\(^45\), again potentially affecting the outcome. Others have raised the concerns about the possibility of infection hazards to laboratory personnel from extracted human teeth being tested\(^2\)\(^46\),\(^2\)\(^47\).

In general, orthodontic bonding to enamel may involve a combination of the following\(^2\)\(^45\):

1. Penetration of the initially fluid material into the etched enamel and formation of resin tags after polymerisation;

2. Development of strongly bonded surface precipitates, which serve as a substrate to which resin can be mechanically retained or chemically bonded;

3. Chemical bonding to the calcium ion of the hydroxyapatite crystal, which is employed in many approaches including polycarboxylate or phosphate ionic binding.
An artificial substrate that was flat and mimicked the bonding potential of enamel would be a step in the right direction for standardisation of orthodontic bond testing. Klocke et al. investigated the suitability of different synthetic calcium phosphate based substrates as a biometric enamel surface model for orthodontic bond testing. They found that by hot pressing and sintering a carbonated hydroxyapatite substrate could be synthesised that resulted in shear bond strengths comparable with human enamel. The amorphous and cold pressed carbonated hydroxyapatite exhibited fractures within the substrate on debonding. The mean bond strength values for the carbonated hydroxyapatite were 7.38 MPa (sd 1.75) for specimens pressed at 300°C and 9.55 MPa (sd 2.23) for specimens pressed at 300°C then sintered at 600°C. The addition of a Sodium Fluoride treatment after sintering resulted in a lower bond strength (mean 6.52 MPa, sd 1.03).

(G) Fluoride content of the tooth

One of the risks of orthodontic treatment is the loss of mineral causing white spot or carious lesions. The area of etched enamel around the bonded brackets is an area that is susceptible to such lesions. It is known that incorporation of fluoride into the enamel structure as fluoroapatite (Ca$_5$(PO$_4$)$_3$F) can result in remineralisation of small decalcified or carious lesions and also reduce the formation of new lesions. Apart from topical fluoride treatment during orthodontic treatment it has been suggested that fluoride application before etching, during etching or after etching may reduce
the chance of problems; however, they may also affect the bond strength of the orthodontic brackets.

The application of fluoride before etching has been tested with APF, stannous fluoride, duraphat and sodium fluoride paste\textsuperscript{249-251}. The use of these agents before bonding did not adversely affect the bond strength. However, one study\textsuperscript{251} reported that at debond there was an increased incidence of enamel fracture after use of an APF gel before bonding. Fluoride may be applied while etching by incorporating APF or sodium fluoride into the etchant\textsuperscript{108,252,253}. The addition of fluoride to the etchant does not impede the effect of the etchant with the bond strengths of the fluoride incorporated etches being equivalent to the non-fluoride etches. There appears to be no enamel detachment on debonding with 1.23% sodium fluoride added and etching for 15 seconds\textsuperscript{252}. When APF incorporated gel is used for 30 seconds, the failure point transfers from bracket-resin interface to enamel-resin interface with increasing concentration, therefore the authors recommended a 50% or 67% APF fraction to reduce the risk of enamel damage\textsuperscript{108}.

Fluoride applied after etching has been investigated by Hirce \textit{et al.}\textsuperscript{254}. They applied a basic phosphate fluoride for 3 minutes and a stannous fluoride for 4 minutes after etching and before the application of the sealant and found that neither affected the bond strength.

In terms of teeth that already have a high fluoride content, ones affected by fluorosis, it is possible that the increased fluoride content of the surface may reduce the effectiveness of the etch and therefore result in a lower bond strength. Ng'ang'a \textit{et}
assessed the etch pattern, bond strength and bond failure site of orthodontic
brackets bonded to fluorotic and nonfluorotic teeth. They found that etching with
40% phosphoric acid for 60 seconds produced a variety of patterns comparable with
those obtained after similar treatment to nonfluorotic enamel with no difference in the
bond strength.

(H) Disinfection and storage media of tooth before bonding.
In in vitro research it is necessary to maintain the physiologic condition of the teeth
as close as possible to that in vivo. The literature reports a number of sterilising
methods, storage media and time frames between collection of the test teeth and their
bonding. If it has a significant effect then bond strength studies should be restricted to
examining recently extracted teeth to generate meaningful results. However
existing literature has done little to address this problem with most bond strength
studies using “freshly extracted” teeth or teeth extracted for not more than a specified
time. With the current decline in availability of such teeth the scope and convenience
of bond strength investigations could be limited.

It has been reported that enamel specimens stored in physiologic saline were softer
than corresponding specimens stored in water (Muhlemann, 1964) and that
formaldehyde is inappropriate as a storage solution for enamel studies as it is easily
oxidised to formic acid which may affect the pH of the storage solution (Silverstone,
1967). Habelitz et al. using nanoindentation techniques showed that there was a
20% and 30% reduction in the elastic modulus and hardness of enamel and dentine after 1 day of storage in deionised water. However, Poolthong\textsuperscript{258} found no difference in hardness when storing teeth in deionised water for up to 3 months. It is possible that softer enamel may result in a reduced bond strength. De Jong \textit{et al.}\textsuperscript{259} concluded that enamel stored in water for one week had a measurable change in contact angle; the measurable change happened in the first week of storage. This change in contact angle may influence \textit{in vitro} experiments as the change may be due to deterioration of those organic materials and/or the leaching out of the enamel small organic or inorganic molecules. However, Williams and Svare\textsuperscript{256} demonstrated that the bond strength of teeth stored in distilled water and thymol at 4°C for 24 hours, 3 months and 5 years was not significantly different.

(I) Elapsed time following bonding.

In orthodontic bond strength testing there is a wide variety of media used between bonding and testing, with very few studies testing these parameters. Nagel (1975)\textsuperscript{260} tested specimens at 24 hours and 1 month and concluded that there was no deterioration of bond strength. Reynolds and von Fraunhofer (1976)\textsuperscript{261} found that bond strengths did not vary significantly when specimens were tested at 3 hours and at 6 months. Tavas and Watts (1984)\textsuperscript{262} concluded that bond strength increased from 5 minutes to 24 hours and therefore timing is not critical as long as it is not less than 24 hours. The problem is that \textit{in vivo} brackets are put under forces almost
immediately. In terms of the post-bonding storage media, specimens kept in saline have been shown to have softer enamel compared to specimens stored in distilled water\textsuperscript{24}. Fox \textit{et al.}\textsuperscript{24} reported that the effect of temperature on the storage media has not been tested, but the majority of papers use water at 37\textdegree{}C for 24 hours and that in the absence of any evidence this adversely affects bond strength suggest this should be the media used in all studies. Brosh \emph{et al.}\textsuperscript{263} compared the bond strength of brackets bonded on premolars that had been stored for 48 hours or 12 months in 100\% humidity at 37\textdegree{}C. They found that the storage time before testing did not affect the bond strength or the adhesive remnant index.

Bleaching of teeth prior to bonding has been shown to reduce the bond strength\textsuperscript{205,264}. Ruse \textit{et al.}\textsuperscript{265} found increased nitrogen concentration when bovine enamel was immersed in hydrogen peroxide for 60 minutes. However, they concluded that the reduction in bond strength was not related to peroxide induced change in the elemental composition of the surface enamel. Lai \textit{et al.}\textsuperscript{266} also found a reduced bond strength for composite when teeth were bleached with carbamide peroxide gel. They indicated that the reduction in bond strength was due to free radicals in the polymerisation causing oxygen release from the hydrogen peroxide in the surface of the enamel. Extrapolating from these studies suggests that teeth stored in a hypochlorite solution may have a reduced bond strength due to the storage solution. However immersion of the bleached teeth in water for a week before bonding results in a return to control bond strength\textsuperscript{205}. Treatment of the tooth by carbamide peroxide
followed by immersion for 3 hours in 10% sodium ascorbate solution has also been shown to increase the bond strength to similar levels as control teeth stored in distilled water\textsuperscript{266}.

Matasa\textsuperscript{267} has proposed that biodegradation of the adhesive can contribute to failure of the bond between the tooth and the bracket. Studies of composite degradation have led to a number of theories, which are not mutually exclusive and listed below\textsuperscript{268}:

- Unreacted composite acrylic leaches from the composite when it is immersed in water.

- Water can hydrolyse the acrylic, particularly at the surface layers and the interface of the acrylic and filler particles. It can also hydrolyse the filler particles themselves. This hydrolysis of composites is enhanced in artificial saliva.

- Composite degrades in the presence of food simulants such as ethanol, probably because of reactions with the alcohol hydroxyl group or molecular oxygen. The exposure to food simulants has been shown to weaken the bond strength.

- Non-specific porcine liver esterases enhance degradation because of enzymatic hydrolysis.

- Composite degrades in natural saliva and \textit{in vitro}, probably as a combination of hydrolysis and enzymatic hydrolysis.

- Certain bacteria can consume composite, using it as a source of carbon.

It has been known for some time that dental composites are prone to degradation due to hydrolysis but this softening and degradation has not been associated with
increased bond failure in orthodontics as the average treatment duration is much less than the life expectancy of a dental restoration. It has also been shown that Bis-GMA based composites are susceptible to chemical softening by certain solvents. Lee et al. found that exposure to ethanol for 30 days significantly decreased the bond strength and Hobson et al. found the exposure to a 50% ethanol solution over 12 weeks, simulating alcoholic food, significantly reduced the bond strength of Transbond from 10.0 MPa to 5.9 MPa. They concluded that alcohol exposure from drinks or mouthwash may affect in vivo bond strength.

Oncag et al. compared the shear bond strength of teeth subjected to daily acidic drinks in vitro and in vivo and found that they have a negative effect on bracket retention, suggesting that if samples are stored in an acidic solution it can affect the bond strength measured. Murray and Hobson bonded brackets with Transbond or Heliosit to enamel slabs embedded in removable appliances, which were then worn by 20 volunteers. The shear bond strengths were compared to controls stored in water at 37°C at 4, 8 and 12 weeks. They found that the in vivo bond strength of Transbond was significantly reduced at 4 weeks, and Heliosit at 4 weeks and 8 weeks. However, there was no difference at the other times tested. This suggests that in vitro studies where the sample has been stored for longer than 8 weeks may demonstrate lower bond strengths, with distilled water not accurately representing the oral environment.
(J) Configuration of specimen testing jig/ type of loading

The method for controlling the debonding force is poorly defined, producing results with a wide variation\textsuperscript{22}. The mode of testing varies between studies; it can be tensile, shear, tensile and shear, tensile torsion or tensile/ peel\textsuperscript{41}, with early research paying little attention to the exact direction of the debonding force. It has been recognised that the direction of the force will affect the results obtained as the stress distributions within the adhesive differ according to the method of loading, which would influence the strength measurements\textsuperscript{22,272}. Ideally the direction of pull should be parallel to the bonding surface in shear testing and perpendicular to the bonding surface in tensile testing. However for shear testing the test typically involves a combination of shear and peel because the force is applied at a distance from the bonding surface. Some studies report the point of application as the bracket base, the area of the ligature groove or at the tie wings, which represent different points of application.

Fox \textit{et al.}\textsuperscript{24}, in a critique of bond testing, reported that the majority of tests are in shear. Littlewood and Redhead\textsuperscript{22} recommended a jig be used to set up the brackets on the teeth and a second jig to debond the brackets. They compared the shear bond strength of metal brackets bonded and debonded with and without the use of jigs. The mean bond strength was greater with the jigs (8.55 MPa, sd 1.8) than without (4.57 MPa, sd 3.65) and the Weibull modulus and characteristic strength were significantly higher in the jig group (5.236 cf 1.871 and 9.266 cf 5.145). There was a lower spread of failure and a higher level at which 63.2% fail. Therefore, it is likely that the use of
jigs would improve standardisation and reproducibility.

Thomas et al.\textsuperscript{273} in a 3D finite element analysis demonstrated a 48% difference in shear stress generated between forces applied at the enamel surface and forces applied at 300\textmu m. Klocke and Kahl-Nieke\textsuperscript{274} compared the shear bond strength of metal orthodontic brackets debonded with the point of force application at the bracket base, ligature groove and the tie wings. They found that the debonding force location had a significant effect on shear bond strength measurement and the bond failure pattern with the mean bond strengths at the bracket base (22.70 MPa, sd 4.23), ligature groove (11.52 MPa, sd 2.74) and at the tie wings (9.44 MPa, sd 2.96). The shear bond strength reduced 49.3% when the point of application moved from the bracket base to the ligature area and 58.5% when moved from the bracket base to the tie wings. This demonstrates that the point of application is an important factor in bond strength testing.

In a second study, Klocke and Kahl-Nieke\textsuperscript{275} looked at the actual direction of the applied force and compared 15\textdegree towards the enamel, 0\textdegree, 15\textdegree, 30\textdegree and 45\textdegree away from the enamel surface. They found that the shear bond strengths were significantly affected by the direction of the debonding force with the greatest shear bond strength when the direction was toward the enamel (22.9 MPa, sd 1.72) and the least at 45\textdegree away from the enamel surface (6.65 MPa, sd 1.14). The bond failure mode was also affected with more adhesive left on the teeth when the direction was furthest from the enamel. This shows the importance of direction as a factor in bond strength testing.
In terms of tension, a change in direction has only been estimated by finite element analysis. Katona and Moore found that if all of the tensile load is placed on one wing of the bracket that the stress components nearly double in magnitude. Thomas et al. found that tensile stresses were less sensitive to angulation errors.

In conclusion tension and shear are the test methods usually used in orthodontic bond testing but investigators should remember that the configuration of the test influences whether other aspects such as peel or torsion influence the results. The goal in reporting should be to achieve a coefficient of variation (standard deviation/mean) in the range of 20-30%. McCabe and Carrick suggested that a Weibull survival analysis should be used for testing of dental materials as this method does not require a normally distributed sample and focuses on the tail of the sample, the smaller values, thereby providing more emphasis on the safety of the bonding system.

**The Weibull Analysis**

Orthodontic bonding adhesives are brittle and can produce a wide scatter of bond strength data, which may not conform to a normal distribution. Most studies quote the mean bond strength, which is used as a gauge for the amount of force necessary to dislodge the bracket clinically. However, it is in fact the lowest value of the bond strength that governs the likelihood of clinical failure and the weaker values (the tail of the distribution) are more important. The Weibull analysis, a survival analysis,
enables the researcher to come to a more realistic evaluation of the bond strength than can be achieved by using a normal distribution\textsuperscript{34,41}. The Weibull equation depends on two parameters\textsuperscript{277}:

(1) \textit{The Weibull Modulus}. This can be compared to a standard deviation of a normal distribution. A low Weibull modulus indicates a wide scatter in the experimental data. A high Weibull modulus indicates a close grouping of the fracture stress values and a high reliability of the samples.

(2) \textit{The characteristic level}. This refers to the stress at which 63.2 per cent of the sample fail. The characteristic level is similar to the mean value of a normal distribution. The higher the characteristic level the higher the bond strength of a bracket-bonding system.

The Weibull analysis shows that there is a certain probability of bond failure at a low force even with a high mean strength. It may actually be preferable to choose a bracket with a lower mean strength but a higher Weibull modulus, which would indicate a closer grouping of the data and a shorter tail of bond fractures at low stress.

Due to the wide scatter of the bond strength data it is necessary to test at least 20-30 specimens to predict performance of a bracket bonding system accurately with the Weibull analysis\textsuperscript{276}.
The Weibull distribution is based on the following equation relating the probability of failure \((P_f)\) to stress \((\sigma)\):

\[
\ln \{\ln[1/(1-P_f)]\} = m \ln \sigma - m \ln \sigma_0
\]

Where \(\ln\) is natural logarithm.

This can be expressed in the form of a linear graph with the formula:

\[
y = mx + c
\]

where \(y = \ln\{\ln[1/(1-P_f)]\}\), \(x = \ln \sigma\), \(c = -m \ln \sigma_0\) (intersect of the \(y\) axis).

The slope of the graph, \(m\), gives the Weibull modulus and the intersection of the line with the \(y\)-axis allows calculation of \(\sigma_0\), the characteristic strength.
(K) Crosshead speed of mechanical testing machine

One of the variables in bond strength testing is the rate of force application, which is determined by the crosshead speed of the loading plate. Unfortunately, this has not been standardised in studies making inter study comparison difficult. It has been suggested that the loading plate be set at 0.5mm/min for consistency. However, it should be noted that this value does not reflect clinical conditions, where in vivo debonding incidents are expected to occur at a much higher impact velocity, where viscoelastic behaviour of the adhesive, which may be important at low crosshead speeds is largely absent. Lindemuth and Hagge reviewed studies from the 1996 and 1997 International Association for Dental Research general sessions and noted a range from 0.05mm/min to 50mm/min. Al-Salehi and Burke reviewed bond testing
to dentine and found for shear bond strength testing to dentine, the range of the most common loading rate was 5mm/min. When the orthodontic literature is reviewed there seems to be a range of 0.5-5mm/min with 0.5mm/min the most common. Fox et al.\textsuperscript{24} suggested a crosshead speed of 0.1mm/min as part of their suggested protocol for bond testing.

It had been previously speculated\textsuperscript{278} that lower crosshead speeds may allow the composite to act as viscoelastic material, deforming more as the increased pressure is applied resulting in a higher shear bond strength. A higher shear bond strength may also occur at higher crosshead speeds, as the resin may act as a brittle solid, with increased energy directed towards fracture of the specimen rather than molecular deformation and flexure. Hara et al.\textsuperscript{280} found that crosshead speed affected mode of failure and concluded that crosshead speeds of 0.5 and 0.75mm/min result in more adhesive fractures and are therefore more preferable. They also indicated that high crosshead speeds may develop abnormal stress distributions during the shear test, including cohesive failures in the enamel and the resin-based composite, which would influence the bond strength values achieved.

Klocke and Kahl-Nieke\textsuperscript{281} bonded stainless steel brackets to 120 bovine incisors and looked at the shear bond strengths, Weibull analysis and ARI at crosshead speeds of 0.1, 0.5, 1.0 and 5.0mm/min. They found that crosshead speed does not seem to influence the debonding force or failure modes. Bishara et al.\textsuperscript{282} tested the shear bond strength of brackets at a cross head speed of 5.0mm/min and 0.5mm/min and found that there was a significant difference between the two groups with the slower
crosshead speed demonstrating a higher bond strength (12.2 MPa cf 7.0MPa). This was an increase in bond strength of 57% with a reduction in the standard deviation from 66% to 33%. This emphasises the need to standardise test protocols.

(L) Bonded area of the bracket/ bracket base design

All brackets should form bonds of sufficient strength to enamel, yet be capable of being debonded with relative ease and without damage to the underlying enamel surface. Bracket base retention can be mechanical, chemical or a combination of chemical and mechanical. The bond strength of metal brackets is predominantly based on mechanical mechanisms, while ceramic (silane coating) and plastic (plastic primer) brackets use a combination of mechanical and chemical.

The most common method of attachment is mechanical and is generally provided by the adhesive flowing into mechanical undercuts before polymerisation. The undercut on most metal brackets is provided by a brazed fine mesh (Matassa\textsuperscript{283}), which may range in size from 40\textmu m to 110\textmu m and be single or double. Other brackets have milled undercuts or are sandblasted, chemically etched or sintered with porous metal powder\textsuperscript{284}. As brackets have become more aesthetic, they have been decreasing in size with the size of the mesh pad reducing about 75\%\textsuperscript{285}. This decrease in size should have theoretically increased the number of debonded brackets clinically but the manufacturers have improved their designs and adhesives resulting in satisfactory bond strength.
For good mechanical attachment we need good penetration of the adhesive into the undercut areas followed by effective polymerisation. The polymerisation of the adhesive may be affected by the design of the base, especially if it is light cured and the base design does not allow adequate penetration. Two factors that affect the penetration of the adhesive are:

(1) The adhesive itself. Stainless steel bracket bases are hydrophilic (covered by a layer of chromium oxide) with the resin-based adhesives being hydrophobic. Therefore, they take a long time to penetrate the mesh and may not completely penetrate the mesh.\(^{285}\)

(2) The mesh pattern can vary between bracket bases. The important aspects of mesh design are:
- The mesh number, i.e., the number of openings per lineal inch measured from the centre of the wire to the centre of the wire.
- The diameter of the wire, which is important because if it is too thin it could break and if too thick could limit the penetration of the adhesive.
- The size of the aperture (open area) as the higher the percentage of open area the better the penetration of the adhesive.

Lopez\(^{286}\) compared the bond strength of 16 commercially available brackets at 24 hours and 30 days after bonding and found that there was no difference in bond strength at 24 hours and 30 days. The solid bases with perforations around the
periphery generally had the lowest mean shear bond strengths. The bond strength of the foil mesh designs ranged from the most inferior to most superior, with the broad range perhaps relating to the type of mesh and the type of weld to the base. The diameter and aperture of the mesh has been shown to affect the retention of the adhesive to the mesh. In a similar study, Dickinson and Powers tested the tensile bond strength of fourteen bases and found that the bond strength was independent of the nominal area and mesh size. They also found that there was a difference between the two adhesives used and that bases that had spot welds on the base performed less well than identical mesh designs with no spot welds on the base. The spot welds may decrease the nominal area for retention and set up an area of stress concentration, which can initiate fracture of the adhesive at the adhesive-base interface. Sheykholeslam and Brandt reported the problem raised by having a spot weld on the base. Maijer compared four premolar brackets and concluded from the shear bond strengths and SEM data that weld spots reduce retentive area and should be avoided on the edges of attachment bases to prevent poor marginal seal. Moreover, weld spurs reduced the bond strength in some foil mesh samples, bracket bases should be designed to prevent air entrapment under the base and the best resin penetration and bond strength is achieved with a fine mesh base. These early studies support the idea that foil mesh had the best retention, depending on the size of the foil and the number of weld spots. However, the foil mesh used was an open foil and therefore different from a modern orthodontic brackets. Thanos et al. compared the bond strength under shear, tension and torsion for different mesh designs and a
perforated metal base with five different adhesives and found that different adhesive and bracket combinations performed differently under the different test conditions. The mesh base brackets performed best in tension and the perforated base in shear testing. The different adhesives used provided different levels of retention, Therefore they concluded that a bracket adhesive system cannot be selected on the basis of one test.

Coating the bases with a porous metal powder has been investigated by Hanson et al. and Smith and Maijer. Both studies found that the porous metal bases increased the bond strength significantly with a the latter study finding that a coarser structure offers more open pores and provides a higher bond strength. Siomka and Powers compared three types of metal bases (mesh, photo-etched and grooved) bonded after treating the base with etching, silanation, surface activation, etching plus silanation, etching plus surface activation and non treatment as a control. They found that surface treatments did not significantly improve the bond strength of the photo-etched base but etching improved the grooved bracket bond strength by 56% and silanation improved the bond strength of the mesh bracket by 28%.

Willems et al. compared 17 bracket bases under shear/peel and found that the type of bracket base determines its adhesive capacity. The chemical bond of the Allure Accu Arch, a ceramic bracket, performed the best overall with a mean bond strength of 13.9MPa with the worst the CeramaFlex Advant Edge (TP Orthodontics), a plastic bracket, with a mean of 1.6MPa. The metal brackets Mini masters (American Orthodontics) and Omni Arch (Rocky Mountain Orthodontics) had a bond strength
similar to the Accu Arch (GAC). However, the Masters (American Orthodontics) (11.4 MPa) had a lower bond strength than the Mini masters (13.0 MPa), which has more densely packed mesh with a bilayered design demonstrating that the size of the mesh may not play a role in the overall retentive capacity.

MacColl et al.\textsuperscript{293} compared the bond strength of foil mesh brackets of varying sizes after microetching by the manufacturer or sandblasted at the chair side. They found that both techniques produced an enhanced bond. They also demonstrated that bracket bases of 6.82 mm\textsuperscript{2} provided adequate retention. It is possible that bracket base morphology can influence the strength of the cement interface by determining the geometry (depth, size, and distribution) of the cement tags and stress distribution within the bracket interface. The penetration of light, and polymerisation of light activated materials could be influenced by the base morphology. Therefore Knox et al.\textsuperscript{4} compared the bond strength of different bracket bases with four different adhesives and found that the bases do have different bond strengths depending on what adhesive is used. There appear to be certain combinations of adhesive and bracket base that perform optimally. However, the milled bases (Dynalock and Minitwin, 3M Unitek) performed equally well with all the cements, perhaps reflecting better light penetration. Whereas for the mesh bases the chemically cured cements performed better than the light cure cements, which may reflect the fact that 2 brackets were placed together and this may have affected the penetration of the light reducing the cure. Knox et al.\textsuperscript{294} using a finite element analysis compared single and double mesh brackets and concluded that alterations in the wire diameter and
spacing in the single mesh design affects the stress distribution. The double mesh design has a reduced stress at the cement bracket interface due to the fact the inner layer of mesh is stiffer and attracts most of the bending stress, shielding the coarser outer layer.

Sorel et al.\textsuperscript{295} compared the bond strength of a bracket with a laser structured base (Discovery, Dentaureum) and a bracket with a simple foil mesh base (Minitrim, Dentaureum). They found that the laser-structured base provided significantly greater bond strength (17.1 cf 8.7 MPa). The ARI demonstrated that the laser-structured base had more adhesive on the bracket base at debond, which could indicate an increased risk of enamel fracture, however there were no difference in the enamel detachment index between the two brackets.

Sharma-Sayal et al.\textsuperscript{296} compared the bond strength of 6 different bracket bases at 1 hour and 24 hours bonded to bovine teeth with Transbond XT. They found that the base design affected the bond strength with a 60-gauge foil mesh and the undercut-machined base having the highest bond strength.

Bisahra et al.\textsuperscript{297} compared a bracket with a single mesh base and a double mesh base and found that the bond strengths were not significantly different.

Wang et al.\textsuperscript{298} compared the bond strength of 6 brackets with different base designs and found that the size and design of the bracket base affected the bond strength. The circular pattern of the Tomy bracket had the highest bond strength (9.32MPa) possibly due to the circular design allowing air to escape so the composite can penetrate the circular concavities. The larger the mesh type the greater the bond
strength with the Dentaurum larger mesh having a bond strength 8.56MPa and the Ormco smaller mesh bond strength 3.81MPa. However Concise, which is a highly filled resin, was used and that may have affected the penetration into the smaller mesh.

Ozer and Arici\textsuperscript{14}, in a split mouth design, compared the failure rate of brackets after sandblasting the base prior to bonding and using a resin modified glass ionomer cement. They found that over 20 months there was no significant difference in the failure rates (sandblasted 4.9\%, non-sandblasted 4.3\%).

As discussed earlier, bond strength is reported in different units with most modern papers reporting it in MegaPascals (Newtons per millimetre squared). It is important to determine the actual size of the bracket base as a bracket with a larger base may have a lower reported “mean bond strength” but require more force to dislodge it clinically. Cozza et al.\textsuperscript{299} demonstrated this when they compared five brackets with different retentive bases (mesh foil, grooved, waffle base and laser structured). They found that all of the brackets had acceptable clinical bond strength and that when the bond strength was expressed as MPa and in Newtons different brackets had the highest values. They concluded that the surface area of the bracket base can affect the load carrying capacity. The Mini Spirit (Forestadent) has a base surface area of 5.9mm\textsuperscript{2} and had a clinically acceptable bond strength 200N (33MPa) demonstrating that even though an increased area of a bracket base may give greater bond strength a smaller base can be clinically effective.

However, the sizes of the base may not affect the bond strength. MacColl et al.\textsuperscript{293}
compared the bond strength of foil mesh brackets of varying sizes after microetching by the manufacturer or sandblasted at the chair side. They found that there was no significant difference between bracket bases 12.35mm$^2$ and bases of 6.82mm$^2$ with both providing adequate retention.

(M) Type of bracket

There are four types of orthodontic brackets available$^{291}$:

(1) Plastic (for example polycarbonate brackets).
(2) Plastic with metal re-enforced endoskeleton.
(3) Metal
(4) Ceramic

The plastic brackets can achieve high bond strengths through molecular union with resin adhesive, but the bond can be erratic and the attachments themselves have a low strength and rigidity. The ceramic bases, like the metal bases bond through mechanical retention, but may be bulky and brittle. Metal brackets have been the most reliable and are the most commonly used bracket.

Plastic Brackets

Plastic brackets are typically polycarbonate, although some are reinforced with fibreglass, glass particles or metal$^2$. Initially they were well received but were found to suffer from several problems such as distortion following water absorption,
fracture, wear, discolouration, an inability to withstand torquing forces generated by rectangular wires and a lower bond strength.\textsuperscript{20,300}

Dobrin \textit{et al.}\textsuperscript{301} reported high deformation and low torque values with brackets made from polycarbonate only. These problems were confirmed in a study by Feldner \textit{et al.}\textsuperscript{302} who tested four types of polycarbonate brackets (pure, metal slot reinforced, ceramic reinforced and ceramic plus metal slot reinforced) and found that they all had higher deformation and lower torque when compared to metal brackets. They concluded that only the metal slot reinforced brackets were capable of sufficiently torquing the teeth.

Initially, plastic brackets relied on a chemical bond to the tooth surface and relied on the application of a plastic primer. Subsequent modifications of the bracket design and base morphology, such as strengthening the plastic bracket with a metal slot\textsuperscript{302} and making mechanical undercuts on the base have alleviated some of the problems. Buzzita \textit{et al.}\textsuperscript{33} evaluated the tensile bond strength of plastic brackets with highly filled, lightly filled and unfilled resins bonded to plastic cylinders. They found that the plastic brackets had a higher bond strength with the unfilled acrylic cement and highly filled Bis-GMA resin. All of the plastic only bracket samples failed at the viewings, whereas the metal reinforced brackets had fewer within-bracket failures. An earlier study\textsuperscript{303} concluded that Bis-GMA cements did not bond to plastic and the addition of the primers in this study may have resulted in an acceptable bond
strength. The effectiveness of the plastic primer was demonstrated by Akin-Nergiz et al.\textsuperscript{304} when they tested a polycarbonate bracket with 14 adhesive combinations. They found that the diacrylate cements with a plastic primer had a significantly greater bond strength than the same adhesives with no primer. Some of the plastic brackets bonded with primer and either no-mix diacrylate or powder-liquid acrylic resin had the same bond strength as metal brackets, with the adhesive “Quasar” causing enamel fracture if used with plastic brackets as the bond strength was the highest due to the catalyst affecting the chemical adhesion between the bracket/adhesive interface. Overall, the variation in bond strength emphasises the need to consider the specific bracket and adhesive combinations when bonding clinically.

De Paulido and Powers\textsuperscript{305} demonstrated that the bond strength of plastic brackets was significantly lower if primer wasn’t used. They found that without the use of primer the diacrylate cements did not bond to the plastic brackets, which is similar to other studies\textsuperscript{303}, emphasising the importance of the plastic primer for chemical adhesion. The use of a plastic primer does not necessarily result in a clinically acceptable bond strength with Crow\textsuperscript{306} demonstrating low bond strengths with a fibreglass reinforced bracket even with the use of plastic primer. There was a trend for greater bond strength with the plastic conditioner but there was no statistically significant increase. In contrast two studies\textsuperscript{307,308} have shown that the Spirit metal reinforced plastic bracket with mechanical retention has a clinically acceptable bond strength when used with highly filled diacrylate resin (Concise and Reliance) albeit
significantly lower than metal brackets under the same conditions. Liu et al.\textsuperscript{309} compared the Spirit plastic bracket’s bond strength after 24 hours) with two adhesives, System 1 (a urethane modified dimethacrylate) and Reliance (a highly filled Bis-GMA diacrylate resin). They found that the System 1 had an unacceptable bond strength (4.38 MPa), which was significantly lower than the Reliance (6.31 MPa). To assess immediate bond strength, which is important clinically, Liu et al.\textsuperscript{310} compared the Spirit plastic bracket’s bond strength with the same two adhesives after 30 minutes and 24 hours and found that at both times the System 1 had a lower, clinically unacceptable bond strength compared to the Reliance, once again demonstrating the importance of bracket and adhesive combinations. Guan et al.\textsuperscript{311} compared the bond strength of four plastic brackets with different filler contents and found that they all had a lower bond strength than metal brackets. The use of plastic primer did not significantly increase the bond strength and that the filler content tended to correspond to bond strength. Therefore the exposed fillers may influence the bond strength. Following up on the concept of accessing the filler content for chemical bonding Guan et al.\textsuperscript{312} sandblasted the bases of two plastic brackets and then applied a silane coupling agent. They found that the bond strength was significantly increased after sandblasting alone but after thermocycling there was no difference in the bond strength. This suggests that it may make little difference clinically but after sandblasting and silane application the bond strength after thermocycling was higher than non-treatment. This was also evident even if the brackets were sandblasted and
had the silane-coupling agent placed 24 hours before bonding, which suggests this may be effective clinically as this would reduce the chair side time.

Bonding plastic brackets to porcelain has been investigated using conventional etch with a primer, hydrofluoric acid and primer, trubochemical silica coating followed by silane coupling, air abrasion and a silane coupling agent, air abrasion followed by a silane coupling agent plus a bonding agent. All of the methods provided an acceptable bond strength with the bond strengths varying according to the preparation technique with the conventional acid etch the weakest (8.5MPa) and the trubochemical silica coating followed by silane coupling the greatest (13.6MPa).

In conclusion, plastic brackets do not perform as well as metal brackets and require a silane coupling agent, mechanical retention and a highly filled diacrylate resin to bond successfully.

**Metal Brackets**

Metal brackets are the most commonly used with their bond strength depending on the preparation of the tooth, bracket type and base design, type of adhesive, method of polymerisation (chemical, light or dual cure), arch wires used and position in the mouth (type of tooth, occlusal interferences). These are all discussed in their relevant section and therefore will not be reviewed here.