J Orofac Orthop (2016) 77:391–399
DOI 10.1007/s00056-016-0046-0

ORIGINAL ARTICLE

Enamel shear bond strength of two orthodontic self-etching bonding systems compared to Transbond™ XT

Scherhaftfestigkeit zweier selbstätzender Bondingsysteme im Vergleich zu Transbond™ XT

Andreas Hellak[1] · Patrick Rusdea[1] · Michael Schauseil[1] · Steffen Stein[1] · Heike Maria Korbmacher-Steiner[1]

Received: 11 August 2015 / Accepted: 21 May 2016 / Published online: 31 August 2016
© Springer-Verlag Berlin Heidelberg 2016

Abstract

Objective The aim of this in vitro study was to compare the shear bond strength (SBS) and Adhesive Remnant Index (ARI) scores of two self-etching no-mix adhesives (Prompt L-Pop™ and Scotchbond™) for orthodontic appliances to the commonly used total etch system Transbond XT™ (in combination with phosphoric acid).

Materials and methods In all, 60 human premolars were randomly divided into three groups of 20 specimens each. In group 1 (control), brackets were bonded with Transbond™ XT primer. Prompt L-Pop™ (group 2) and Scotchbond™ Universal (group 3) were used in the experimental groups. Lower premolar brackets were bonded by light curing the adhesive. After 24 h of storage, the shear bond strength (SBS) was measured using a Zwicki 1120 testing machine. The adhesive remnant index (ARI) was determined under 10× magnification. The Kruskal–Wallis test was used to statistically compare the SBS and the ARI scores.

Results No significant differences in the SBS between any of the experimental groups were detected (group 1: 15.49 ± 3.28 MPa; group 2: 13.89 ± 4.95 MPa; group 3: 14.35 ± 3.56 MPa; $p = 0.489$), nor were there any significant differences in the ARI scores ($p = 0.368$).

Conclusions Using the two self-etching no-mix adhesives (Prompt L-Pop™ and Scotchbond™) for orthodontic appliances does not affect either the SBS or ARI scores in comparison with the commonly used total-etch system Transbond™ XT. In addition, Scotchbond™ Universal supports bonding on all types of surfaces (enamel, metal, composite, and porcelain) with no need for additional primers. It might therefore be helpful for simplifying bonding in orthodontic procedures.

Keywords Orthodontic bonding · Orthodontic procedures · One-step adhesive · Scotchbond™ Universal · Prompt L-Pop™

Zusammenfassung

Ziel Das Ziel dieser Studie war es, die Scherhaftfestigkeit ("shear bond strength", SBS) und den Adhesive Remnant Index (ARI) von 2 selbstätzenden "no-mix" Adhäsiven (Prompt L-Pop™ und Scotchbond™) mit dem häufig verwendeten Totaletch-System Transbond™ XT (in Kombination mit Phosphorsäureätzung) zu vergleichen.

Material und Methoden Insgesamt 60 humane Prämolaren wurden randomisiert in 3 Gruppen à 20 Proben aufgeteilt. In der Gruppe 1 (Kontrollen) wurde der Transbond™ XT Primer verwendet. In den experimentellen Gruppen wurde Prompt L-Pop™ (Gruppe 2) und Scotchbond™ Universal (Gruppe 3) angewendet. Alle Prämolarenbrackets wurden lichthärtend befestigt. Nach einer 24-stündigen Lagerung wurde bei allen Proben mit der Prüfmaschine Zwicki 1120 die Scherhaftfestigkeit gemessen, und unter 10-facher lichtmikroskopischer Vergrößerung wurde der ARI erhoben. Alle Gruppen wurden statistisch mit dem Kruskal–Wallis-Test auf Unterschiede in der Scherhaftfestigkeit und dem ARI Score verglichen.

Ergebnisse Zwischen allen Gruppen konnten keine statistisch signifikanten Unterschiede in der Scherhaftfestigkeit ermittelt werden (Gruppe 1: 15,49 ± 3,28 MPa; Gruppe 2: 13,89 ± 4,95 MPa; Gruppe 3: 14,35 ± 3,56 MPa; p = 0,489). Auch die Auswertung des ARI-Scores zeigte keine signifikanten Unterschiede (p = 0,368).

✉ Andreas Hellak
hellak@med.uni-marburg.de

[1] Department of Orthodontics, University Hospital of Giessen and Marburg, Georg-Voigt-Strasse 3, 35039 Marburg, Germany

Schlussfolgerung Die Verwendung der beiden selbstätzenden "no-mix" Adhäsive (Prompt L-Pop™ und Scotchbond™) zeigte keine signifikanten Unterschiede in der Scherhaftfestigkeit und dem ARI-Score im Vergleich zu dem häufig verwendeten Transbond™ XT in Kombination mit Phosphorsäureätzung. Da Scotchbond™ Universal zusätzlich auch auf künstlichen Oberflächen einen Haftverbund bietet (Metall, Komposite, Keramik) könnte dies den apparativen Aufwand in der kieferorthopädischen Praxis vereinfachen.

Schlüsselwörter Bracketadhäsivtechnik · Kieferorthopädische Verfahren · Ein-Schritt-Haftvermittler · Scotchbond™ Universal · Prompt L-Pop™

Introduction

In everyday clinical practice, it is important to establish treatment procedures that are as effective as possible, time-saving, and not subject to error. One-step adhesives were developed in the prosthetic area of dentistry. They are helpful in reducing the cost and also effort of equipment in orthodontics, as they require fewer substances to ensure adequate bonding. In the last 10 years, growing numbers of adults are undergoing orthodontic treatment. In this patient cohort, bonding must often be conducted on various prosthetic surfaces such as crowns or cavity fillings made of metal, ceramic, or composite. A specific advantage of the one-step adhesive Scotchbond™ Universal is that it contains the monomer dimethacrylate phosphate (MDP). Originating in a field outside orthodontics, it also bonds to materials other than enamel such as metal and ceramic surfaces [25] and was tested in prosthetic studies [25]. With the exception of macroscopic roughening and cleaning, no other preliminary treatments are necessary. The use of Scotchbond™ Universal in particular might help lower material costs in orthodontics, reduce chair-side time, and circumvent the need for hydrofluoric acid.

According to Brantley and Eliades [7], bond strength values of conventional adhesive systems lie between 8 and 30 MPa. Bonding between the adhesive and bracket and between the adhesive and dental enamel is decisive for multibracket appliance treatment. The bond must withstand forces occurring in the moist oral environment and at the end of treatment, be capable of being removed without residue, and without causing damage to the enamel (e.g., cracking or chipping [22]).

The classic bond is created via the acid-etching technique. Preliminary treatment of the enamel with 37 % phosphoric acid leads to micromechanical retention on the enamel surface [8]. Adhesive use makes it possible to moisten the micromechanical retention created to establish a bond with the composite.

Self-etching adhesive systems were introduced as an alternative to the conventional adhesive technique. These systems simplified the technique, as the etching and application of a bonding agent were now combined in a single step. Self-etching adhesive systems vary in their degree of aggressiveness and are divided into three groups: mild, moderate, and highly aggressive [31]. No relationship between the bond and pH value was revealed in light-curing adhesive systems [27, 29]. The one-step adhesive Adper Prompt L-Pop™ is classified as very aggressive and has a pH value under 1, while Scotchbond™ Universal with a pH of 2.7 is one of the mild adhesive systems.

The advantages and disadvantages of these one-step adhesives have been debated in depth in the literature ever since they were first introduced. Potential advantages include minimizing potential errors in application and reducing the time required for procedures [9]. In addition, self-etching adhesives appear to have advantages for use in a moist environment due to the aqueous components in the primer [17]. The shallower etching pattern produced by one-step adhesives means that less dental enamel is dissolved, leading less of the hard tooth structure being lost [15]. When dentin is exposed after cleaning defects, the tooth's heightened sensitivity is less severe after conditioning [31]. A weaker bond is a potential disadvantage [10]. In 2012, Haller and Janke [13, 14] reported that one-step adhesive systems only achieved 30–65 % of the bonding obtained with the conventional enamel etching technique. One reason suggested for weaker bonding was an etching pattern on the enamel that was much less retentive in comparison to phosphoric acid etching.

Adequate bonding is decisive for complication-free treatment with a multibracket appliance. The aim of the present study was therefore to investigate the shear bond strength (SBS) of two one-step adhesive systems (Prompt L-Pop™ and Scotchbond™ Universal) compared to the conventional enamel etching system (Transbond™ XT).

Materials and methods

Bonding was conducted on 60 extracted flat human premolars from young adults. There are numerous testing parameters that influence bonding values. For a good comparison, all parameters were standardized in the present study, except for the adhesive type. According to Laurance-Young et al. [19], human dental enamel is the most appropriate material for testing bond strength. The teeth used had been extracted for dental reasons and obtained from dental and orthodontic practices. Regarding ethical guidelines, this was residual biological material. The patients were informed that their teeth would be used

Advertisement

Tab. 1 Materials used in the study
Tab. 1 In der Studie verwendete Materialien

Material	Manufacturer
Palavit G	Heraeus Kulzer, Wehrheim, Germany
Discovery® brackets # 790-123-00 for tooth 35	Dentaurum, Ispringen, Germany
Transbond™ XT Primer	3 M Unitek Orthodontic Products, Monrovia, CA, USA
Prompt L-Pop™	
Scotchbond™ Universal	
Transbond™ XT Light Cure Adhesive	
Transbond™ XT etching gel	
Zircate® Prophy Paste	Dentsply DeTrey, Constance, Germany
Chloramine T hydrate	Sigma Aldrich Chemistry, Taufkirchen, Munich, Germany
Aqua B.	Braun Melsungen, Melsungen, Germany

Tab. 2 Specific information about the components of the adhesives investigated
Tab. 2 Spezifische Informationen zu den Komponenten der untersuchten Adhäsive

Adhesive	Pack contents and batch identifier
Transbond™ XT	1 Etching gel: 37 % phosphoric acid (3 M Unitek)
	2 Light Cure adhesive primer, batch no. 8FB/712-034
	3 Light Cure adhesive paste, batch no. 8CU
Prompt L-Pop™ Blister	1a Methacrylate phosphoester, bis-GMA, initiator based on camphor quinone, stabilizers
	1b Water, HEMA, polyalkene acid, stabilizers
Scotchbond™ Universal Blister	1a MDP phosphate monomer, dimethacrylate
	1b HEMA, Vitrebond copolymer, filler, ethanol, water, initiators, silane

bis-GMA glycidyl methacrylate, *HEMA* 2-hydroxyethyl methacrylate, *MDP* monomer dimethacrylate phosphate

in the framework of a research project. The enamel surfaces tested were at least twice the size of the adhesive surface of the brackets used. The enamel surfaces were free of caries, had not been subjected to any dental treatment, and displayed no enamel fractures.

The extracted teeth were kept in a 0.5 % tosylchloramide solution at room temperature. The storage period up to the time of testing was less than 6 months. Table 1 provides details on the materials used.

Three adhesive systems were tested:

- Transbond™ XT (3 M Unitek, Monrovia, CA, USA).
- Prompt-L-Pop™ (3 M Unitek, Monrovia, CA, USA).
- Scotchbond™ Universal (3 M Unitek, Monrovia, CA, USA).

Table 2 lists specific information on the components of these adhesives. The teeth were divided into three groups of 20 each [11]. All the materials were used in accordance with the manufacturer's instructions. All teeth were polished with Zircate® Prophy Paste (127 Dentsply De Trey, Konstanz, Germany), rinsed with water and air dried. For light polymerization, only the Elipar™ FreeLight 2 LED lamp was used (3M ESPE, Seefeld, Germany) in the 400–515 nm wavelength range, which meets the DIN 13900-2 standard for the light source.

- In group 1 (the control group), the conventional acid etching technique was applied. The dental enamel was conditioned with 37 % phosphoric acid (3M Unitek, Monrovia, CA, USA) for 20 s and then rinsed and air dried. The Transbond™ XT Primer (3M Unitek, Monrovia, CA, USA) was applied using a foam pellet, thinly dispersed with air and light-cured with the Elipar™ FreeLight 2 LED lamp for 10 s parallel to the surface with a minimum distance.
- In group 2, the self-etching and light-curing adhesive Prompt L-Pop™ was applied to the unconditioned enamel. Following manual activation of the adhesive in the blister pack, it was applied to the dry enamel and rubbed in for 20 s with the single-use applicator. The liquid was then subjected to a gentle air stream for 5 s and light-cured in the same way.
- In group 3, the one-step adhesive Scotchbond™ Universal was used. Following manual activation of the adhesive in the blister pack, it was applied to the unconditioned enamel, rubbed in with the single-use applicator for 20 s, then air dried and also light cured for 10 s in the same manner.

After using the different adhesives on the enamel surface, the Transbond™ XT Light Cure Adhesive (3M Unitek, Monrovia, CA, USA), adhesive paste was applied on the bracket base. To allow better comparability, only discovery® lower premolar steel brackets (Dentaurum, Ispringen, Germany) were used in this study. The average contact area on the bracket base is 12.93 mm^2. Curing was then carried out for 20 s (10 s mesial and 10 s distal) with the same light source.

Before polymerization, the brackets were applied at a pressure of 3 N via a Correx gauge (Haag-Streit, Berne, Switzerland), following the procedure described by Bishara et al. [6]. All test pieces were prepared by one person (P.R.) on one day. The clinical crown was embedded in Palavit G (Heraeus Kulzer, Wehrheim, Germany). The dental crowns were oriented with their vestibular surfaces parallel to the upper end of the test tube. Before shear bond testing, the specimens were stored in de-ionized water at 37 °C for 24 h.

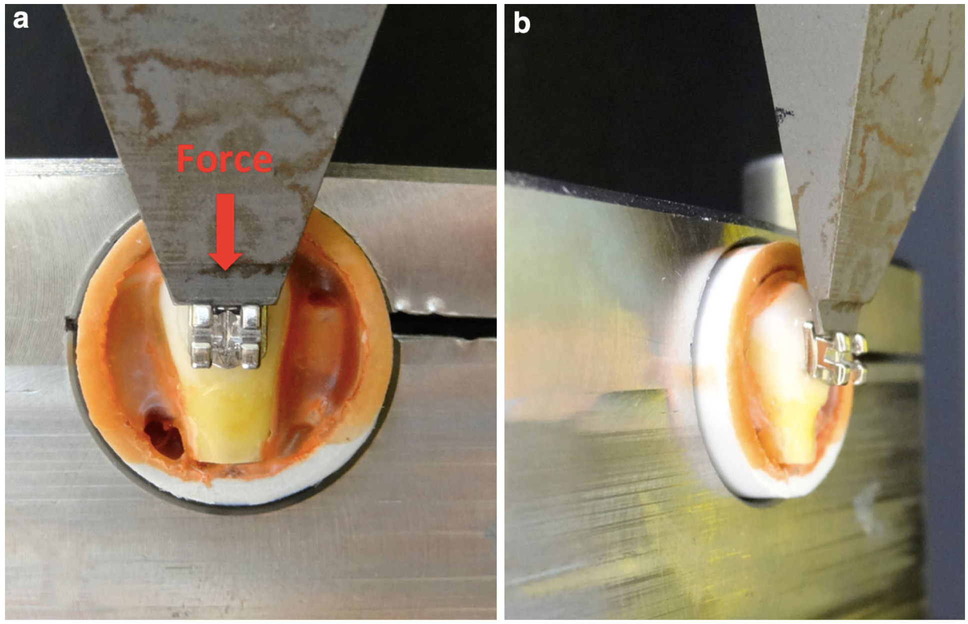

Fig. 1 Hydraulic testing machine Zwicki with installed specimen: **a** frontal view, **b** lateral view
Abb. 1 Hydraulische Prüfmaschine Zwicki mit angebrachter Probe: **a** von vorn, **b** seitliche Ansicht

Shear bond testing was carried out with a standardized, computer-controlled hydraulic testing machine (Fig. 1), the Zwicki 1120.25 (Zwick Ltd., Ulm, Germany). The force velocity introduced was 1 mm/min, and the shearing force was measured in Newtons (N). The residual adhesive left on the base of the bracket and on the tooth surface after shearing off was assessed according to the Adhesive Remnant Index (ARI) [4], which enables bonding failure to be assessed (adhesive rupture versus cohesive rupture). The rupture surfaces were examined under a Leica M420 microscope (Leitz, Wetzlar, Germany) at tenfold magnification.

- An ARI of 0 corresponds to 0 % adhesive on the tooth and 100 % adhesive on the bracket.
- An ARI of 1 corresponds to less than 50 % of the adhesive on the tooth and more than 50 % of it on the bracket.
- An ARI of 2 corresponds to more than 50 % of the adhesive on the tooth and less than 50 % of it on the bracket.
- An ARI of 3 corresponds to 100 % of the adhesive on the tooth and 0 % on the bracket.
- An ARI of 4 means an enamel fracture.

For purposes of better comparability, the resulting forces were converted into MPa in accordance via the following formula:

$$R\left(N/\mathrm{mm}^2\right) = F(N)/A\left(\mathrm{mm}^2\right),$$

with R = cohesive bond strength, F = force, and A = the cross-sectional surface of the adhesive test piece. The calculated value leads to a relative one enabling comparisons with other studies.

Statistical analysis was carried out using IBM SPSS Statistics (IBM, Armonk, NY, USA) for Macintosh, version 21.0. Normal distribution was tested using the Shapiro–Wilk test. Testing with the Shapiro–Wilk test showed that the values were not normally distributed ($p = 0.032$). Nonparametric tests were therefore used. Statistical differences were analyzed using the Kruskal–Wallis test. For testing similarity the Kaplan–Meier survival curve and log rank test were used. The significance level for all of the analysis procedures was set at $p \leq 0.05$.

Results

All three adhesives revealed similar bond strengths (Table 3). The Kruskal–Wallis test exhibited no significant differences between groups. Testing for similarity using the Kaplan–Meier survival curve and log rank test also demonstrated no significant differences in survival distribution (Fig. 2). The Kaplan–Meier curve (Fig. 2) shows that the SBS varies between 10 and 17.5 MPa in 80 % of the samples. Except for the Prompt L-Pop™, all adhesives

Tab. 3 The Kruskal–Wallis test shows no significant differences of sheer bond strength (*SBS*) between the three groups
Tab. 3 Keine signifikanten Unterschiede zwischen den Gruppen hinsichtlich der Scherhaftfestigkeit (*SBS*) im Kruskal–Wallis-Test

Kruskal–Wallis test	SBS (MPa)
Chi square	1.432
Degrees of freedom	2
Asymptotic significance	0.489

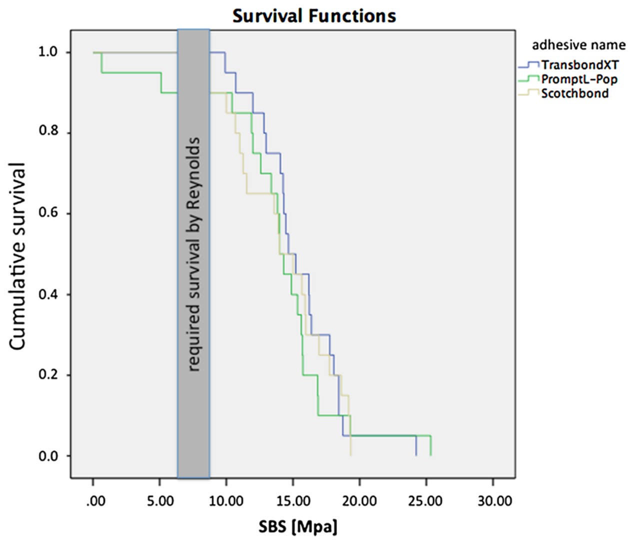

Fig. 2 Kaplan–Meier survival function with the log rank test reveals no significant differences. About 80 % of the samples exhibited a sheer bond strength (*SBS*) between 10 and 17.5 MPa. Except for Prompt L-Pop™, all adhesives yielded greater SBS values than the minimum SBS required by Reynolds [24]. Overall comparisons using the log rank (Mantel–Cox) test: $\chi^2 = 0.392$, 2 degrees of freedom, $p = 0.822$

Abb. 2 In der Kaplan–Meier-Überlebensfunktion mit Log-rank-Test zeigen sich keine signifikanten Unterschiede. Etwa 80 % der Proben zeigten eine Scherhaftfestigkeit (SBS) zwischen 10 und 17,5 MPa. Mit Ausnahme von Prompt L-Pop™ übertrafen die SBS-Werte bei allen Adhäsiven die von Reynolds [24] geforderten Minimalwerte. Vergleiche insgesamt mittels Log-rank-Test (Mantel-Cox): $\chi^2 = 0{,}392$, 2 Freiheitsgrade, p = 0,822

exhibited greater SBS values than the minimum required by Reynolds. In descriptive comparisons, Table 4 shows that the Transbond™ XT adhesive system's shear bond strength was the highest (mean 15.49 N/mm^2). The lowest mean was obtained with the Prompt L-Pop™ (13.89 N/mm^2). The distribution of shear bond strengths in each adhesive system is illustrated in Fig. 3, with stars and circles illustrating outliers.

The type (adhesive versus cohesive) of the bonding failure mode was examined and evaluated under a microscope with tenfold magnification. The frequency distributions in the Adhesive Remnant Index (ARI) are provided in Table 5. It can be seen that ARI values were also similarly distributed. Statistical analysis of the ARI scores' distribution again revealed that they were not normally distributed. The Kruskal–Wallis test demonstrated no significant differences between groups (Table 6). The ARI scores' distribution in conjunction with the different adhesive systems is shown in Fig. 4.

Discussion

All three adhesive systems investigated in this study exhibited greater adhesive strength values than the minimum required by Reynolds for the clinical use of brackets [24]. Our comparisons revealed no significant differences among the three adhesives with regard to shear bond strength. The wide variation in the Prompt-LPop™ (star and circles) might be due to a measurement error. A mistake may have been made when preparing the experimental setup in that group. The view held by several authors that only a weaker bond can be expected has thus been disproved [10].

The Transbond™ XT adhesive system is one of the standard adhesive systems in orthodontics. Many working groups have investigated its adhesive strength [1, 6, 16, 18, 24]. In the present study, we obtained a comparable mean value from the Transbond™ XT adhesive system similar to that reported in other studies for the bracket–adhesive bond [2, 27, 32]. The second bonding system, Prompt L-Pop™, also yielded SBS values similar [9, 28] or higher [3, 5] to those reported in the literature. In comparison to other adhesives like the Clearfil Protect Bond™, all the adhesives we tested showed SBS values [3] similar to or higher than those of the Transbond™ Plus and Futurabond® NR. Scotchbond™ or Scotchbond™ Multipurpose-Plus is not the same as Scotchbond™ Universal although they sound similar. Scotchbond™ Universal is the updated version of Adper™ Easy Bond, which has been available since December 31, 2012. We identified no comparable studies applying a similar study design to test the Scotchbond™ Universal adhesive system, the third adhesive system used in the present study. The literature on the Scotchbond™ Universal only refers to its use in prosthetics. Takamizawa et al. [30] reported much higher SBS values that are not necessary for bracket bonding (28.4–48.6 MPa). Comparison to its use in orthodontics would be difficult because such SBS could trigger enamel fractures during debonding.

Tab. 4 Descriptive statistics on sheer bond strength values for the different bondings used
Tab. 4 Deskriptive Statistik der SBS(Scherhaftigkeit)-Werte bei Verwendung der unterschiedlichen Bondingsysteme

Adhesive	Parameter	*N*	Minimum	Maximum	Mean	Standard deviation
Transbond™ XT	MPa	20	9.91	24.24	15.4905	3.28037
Prompt L-Pop™	MPa	20	0.65	25.33	13.8900	4.94659
Scotchbond™ Universal	MPa	20	8.76	19.33	14.3530	3.55640

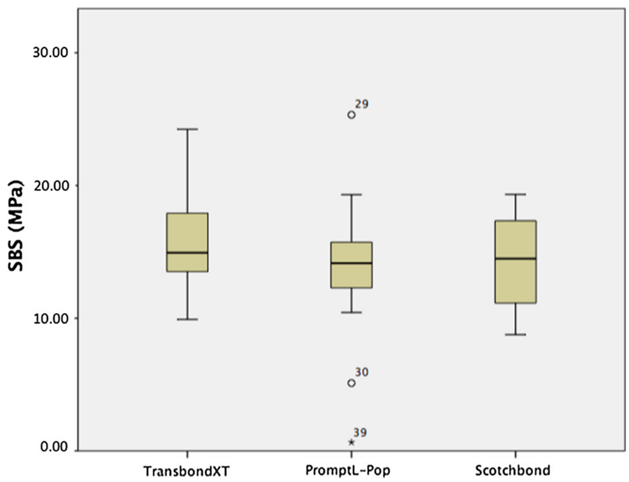

Fig. 3 Distribution of sheer bond strength (SBS) in MPa of the different adhesives used ($n = 60$). All three adhesives demonstrated similar bond strengths. *Stars* and *circles* reveal outliers in the Prompt L-Pop™ group

Abb. 3 Verteilung der Scherhaftfestigkeit (SBS) in MPa bei den verwendeten unterschiedlichen Adhäsiven (n = 60). Bei allen dreien zeigten sich ähnliche Haftfestigkeiten. *Sternchen* und *Kreise* zeigen Ausreißer in der Prompt L-Pop™-Gruppe an

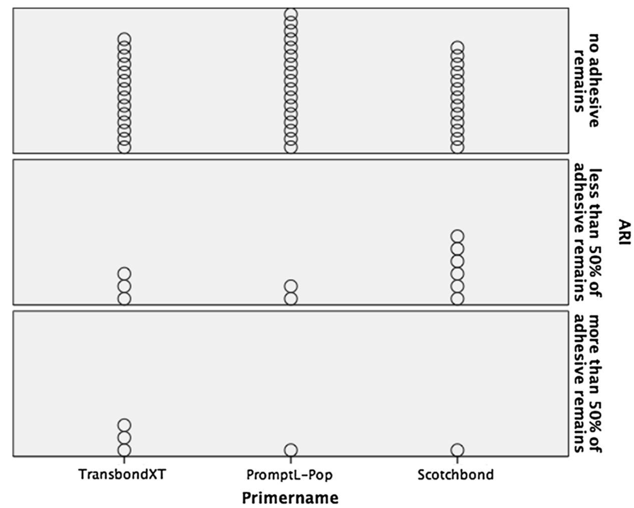

Fig. 4 Distribution of the Adhesive Remnant Index (ARI) scores of the three different adhesives used in this study ($n = 60$). An ARI of 0 = 0 % adhesive on the tooth and 100 % adhesive on the bracket. An ARI of 1 ≤50 % of the adhesive on the tooth and >50 % of it on the bracket. An ARI of 2 ≥50 % of the adhesive on the tooth and <50 % of it on the bracket, and an ARI of 3 = 100 % of the adhesive on the tooth and 0 % on the bracket

Abb. 4 Verteilung der ARI(Adhesive Remnant Index)-Scores auf die 3 verschiedenen Adhäsive (n = 60). ARI 0 bedeutet: 0 % Adhäsiv auf dem Zahn und 100 % Adhäsiv auf dem Bracket; ARI 1: < 50 % Adhäsiv auf dem Zahn und > 50 % auf dem Bracket; ARI 2: > 50 % Adhäsiv auf dem Zahn und < 50 % auf dem Bracket. ARI 3: 100 % Adhäsiv auf dem Zahn und 0 % auf dem Bracket

Tab. 5 Frequency distribution of the adhesive remnant index (ARI)
Tab. 5 Häufigkeitsverteilung der *ARI* (Adhesive Remnant Index)-Scores

Bonding system	ARI score			
	0	1	2	3
Transbond™ XT	14	3	3	0
Prompt L-Pop™	17	2	1	0
Scotchbond™ Universal	13	6	1	0

Tab. 6 The Kruskal–Wallis test shows no significant differences between the adhesive remnant index (ARI) scores
Tab. 6 Keine signifikanten Unterschiede hinsichtlich *ARI*(Adhesive Remnant Index)-Scores im Kruskal–Wallis-Test

Ranking	ARI	
Primer name	*N*	Mean ranking
Transbond™ XT	20	31.95
Prompt L-Pop™	20	27.03
Scotchbond™ Universal	20	32.53
Total	60	
Statistics for the test	ARI	
Chi square	2.001	
Degrees of freedom	2	
Asymptotic significance	0.368	

According to the manufacturer's information, Scotchbond™ Universal contains the monomer MDP, which also bonds adhesively to metal and ceramic surfaces. Scotchbond™ Universal may therefore help lower equipment costs in orthodontics, as fewer substances are required to achieve equally effective adhesive bond strengths with different materials. Eliminating the need for selective etching followed by bond application may reduce both the risk of errors during application and the amount of chair time [12]. Another advantage is that this substance is applicable in a moisty environment due to the aqueous components of the self-etching primer. As hydrophilic adhesive systems repel moisture from the enamel surface, the adhesive can penetrate the conditioned enamel without obstruction [17]. In contrast to conventional adhesive systems, therefore, no absolute drying is required. This has advantages especially when bonding brackets in the inferior and posterior teeth (where more moisture is present that can hamper the bond's efficacy) [20, 21]. The reduced susceptibility to moisture during the adhesion process can facilitate adhesion in the second molars, lower premolars, and exposed teeth, as the enamel surface being bonded is more often contaminated with saliva or even blood. In the presence of moisture or saliva, self-conditioning adhesive

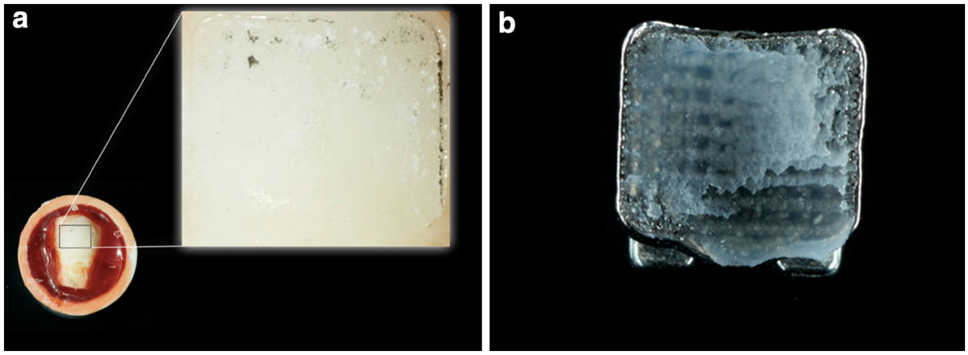

Fig. 5 Representative examples of Adhesive Remnant Index (*ARI*) scores: **a** score 3 indicates 100 % of the adhesive on the tooth/0 % on the bracket and **b** ARI score 0 indicates 0 % of the adhesive on the tooth/100 % adhesive on the bracket

Abb. 5 Repräsentative Beispiele der ARI(Adhesive Remnant Index)-Scores. **a** Score 3 entspricht 100 % Adhäsiv auf dem Zahn/0 % Adhäsiv auf dem Bracket, **b** Score 0 bedeutet 0 % Adhäsiv auf dem Zahn/100 % Adhäsiv auf dem Bracket

systems yield better bond strength than conventional adhesive systems [23, 26].

The shallower etching pattern associated with self-conditioning adhesive systems means less dental enamel is dissolved, meaning less hard tooth tissue is compromised [15]. Hosein et al. [15] reported that while etching enamel with self-conditioning adhesive systems, there was less enamel loss (0.03–0.74 µm) than with conventional adhesive systems (1.11–4.57 µm). Another advantage of this type of adhesive procedure is that the etching depth and depth of penetration do not differ.

In general, the bonding strength of any adhesive system should only suffice to resist the forces arising in the dentition. On the other hand, the bracket must be easily removed without causing iatrogenic damage such as chipping and cracking of the enamel [22]. Unlike the demands made on composite fillings in conservative dentistry, which are meant to remain in place for as long as possible, an adhesive used in orthodontics must be removable at the end of treatment without damaging the teeth. Once the treatment goal has been achieved, a multibracket device must be completely removable. The results of the Adhesive Remnant Index reveal that the three bonding systems' adhesive efficacy is distributed homogeneously. At least 65 % of the tooth–adhesive combinations in all of the bonding systems revealed an ARI value of 0, meaning there is no residual adhesive, or hardly any, on the tooth surfaces, so that the effort needed to remove residual adhesive is minor, and possible without sacrificing dental enamel. In addition, no enamel cracks or fractures were detected. All of the adhesives we tested are thus safe for clinical use (Fig. 5).

Shear bond tests are a recognized in vitro testing procedure for measuring adhesive force. To facilitate comparison of the findings, many authors convert forces to MPa [33]. Numerous testing parameters can influence in vitro adhesiveness values, such as the type of adhesive used, the bracket base's material properties, how the test pieces are stored, the adhesive gap's diameter, the shearing velocity of the test machine, the type and duration of light-curing, and the dental material. All of the other parameters were standardized in this study with the exception of the adhesive type. Variability in how individual human enamel is structured can be disregarded with the number of test samples exceeding 10.

In general, in vitro experimental results are never precisely comparable with those obtained under in vivo situations, since application-sensitive substrates and the complexity of their interactions are subject to error, and standardization can never succeed 100 % [22]. However, in vitro experiments do yield important information for in vivo situations and are of decisive value for clinical practice and everyday clinical use.

Conclusion

Given the limitations of an in vitro investigation, all three of the tested adhesive systems revealed similar bond strength values. One-step adhesives help us carry out treatment procedures that are as effective, time-saving, and error-free as possible. The use of Scotchbond™ Universal in particular could help lower equipment costs in orthodontics, since like the Prompt L-Pop™, it offers all the advantages of a one-step adhesive, but unlike the latter, it also bonds to all surfaces. Further in vivo studies will be needed to obtain clinical confirmation of these promising results.

Acknowledgments The authors are grateful to Dentaurum (Ispringen, Germany) for providing discovery® brackets.

Compliance with ethical guidelines

Conflict of interest A. Hellak, P. Rusdea, M. Schauseil, S. Stein, and H. M. Korbmacher-Steiner declare that they have no competing interests.

This article does not contain any studies with human participants or animals performed by any of the authors.

References

1. Amm EW, Hardan LS, BouSerhal JP, Glasl B, Ludwig B (2008) Shear bond strength of orthodontic brackets bonded with self-etching primer to intact and pre-conditioned human enamel. J Orofac Orthop 69:383–392
2. Anand MK, Majumder K, Venkateswaran S, Krishnaswamy NR (2014) Comparison of shear bond strength of orthodontic brackets bonded using two different hydrophilic primers: an in vitro study. Indian J Dent Res 25:191–196
3. Arhun N, Arman A, Sesen C, Karabulut E, Korkmaz Y, Gokalp S (2006) Shear bond strength of orthodontic brackets with 3 self-etch adhesives. Am J Orthod Dentofac Orthop 129(4):547–550
4. Artun J, Bergland S (1984) Clinical trials with crystal growth conditioning as an alternative to acid-etch enamel pretreatment. Am J Orthod 85:333–340
5. Basaran G, Ozer T, Devecioglu Kama J (2009) Comparison of a recently developed nanofiller self-etching primer adhesive with other self-etching primers and conventional acid etching. Eur J Orthod 31(3):271–275
6. Bishara SE, VonWald L, Laffoon JF, Warren JJ (2001) Effect of a self-etch primer/adhesive on the shear bond strength of orthodontic brackets. Am J Orthod Dentofac Orthop 119:621–624
7. Brantley WA, Eliades T (eds) (2001) Orthodontic materials: scientific and clinical aspects. Thieme, Stuttgart, pp 111–122
8. Buonocore MG (1955) A simple method of increasing the adhesion of acrylic filling materials to enamel surfaces. J Dent Res 34:849–853
9. Cal-Neto JP, Carvalho F, Almeida RCC, Miguel JAM (2006) Evaluation of a new self-etching primer on bracket bond strength in vitro. Angle Orthod 76:466–469
10. De Munck J, Van Landuyt K, Peumans M, Poitevin A, Lambrechts P, Braem M et al (2005) A critical review of the durability of adhesion to tooth tissue: methods and results. J Dent Res 84:118–132
11. Fox NA, McCabe JF, Buckley JG (1994) A critique of bond strength testing in orthodontics. Br J Orthod 21:33–43
12. Haller B, Blunck U (2003) Übersicht und Wertung der aktuellen Bondingsysteme. Zahnärztl Mitt 7:48–58
13. Haller B, Janke F (2012) Sind selbstkonditionierende Bondingsysteme praxistauglich? Und wenn ja, wofür? Teil 1: Grundlagen, Zusammensetzung, Haftmechanismus, Klassifikation. Quintessenz 63:713–820
14. Haller B, Janke F (2012) Sind selbstkonditionierende Bondingsysteme praxistauglich? Und wenn ja, wofür? Teil 2: Indikationsbezogene Bewertung selbstkonditionierender Bondingsysteme. Quintessenz 63:857–869
15. Hosein I, Sherriff M, Ireland AJ (2004) Enamel loss during bonding, debonding, and cleanup with use of a self-etching primer. Am J Orthod Dentofac Orthop 126:717–724
16. Iijima M, Ito S, Yuasa T, Muguruma T, Saito T, Mizoguchi I (2008) Bond strength comparison and scanning electron microscopic evaluation of three orthodontic bonding systems. Dent Mater J 27:392–399
17. Klocke A, Shi J, Kahl-Nieke B, Bismayer U (2003) In vitro investigation of indirect bonding with a hydrophilic primer. Angle Orthod 73:445–450
18. Korbmacher H, Huck L, Adam T, Kahl-Nieke B (2006) Evaluation of an antimicrobial and fluoride-releasing self-etching primer on the shear bond strength of orthodontic brackets. Eur J Orthod 28:457–461
19. Laurance-Young P, Bozec L, Gracia L, Rees G, Lippert F, Lynch RJM et al (2011) A review of the structure of human and bovine dental hard tissues and their physicochemical behaviour in relation to erosive challenge and remineralisation. J Dent 39:266–272
20. Mizrahi E (1982) Success and failure of banding and bonding. A clinical study. Angle Orthod 52:113–117
21. Newman GV (1978) A posttreatment survey of direct bonding of metal brackets. Am J Orthod 74:197–206
22. Pickett KL, Sadowsky PL, Jacobson A, Lacefield W (2001) Orthodontic in vivo bond strength: comparison with in vitro results. Angle Orthod 71:141–148
23. Prasad M, Mohamed S, Nayak K, Shetty SK, Talapaneni AK (2014) Effect of moisture, saliva, and blood contamination on the shear bond strength of brackets bonded with a conventional bonding system and self-etched bonding system. J Nat Sci Biol Med 5:123–129
24. Reynolds IR (1975) Letter: composite filling materials as adhesives in orthodontics. Br Dent J 138:83
25. Sanohkan S, Kukiattrakoon B, Larpboonphol N, Sae-Yib T, Jampa T, Manoppan S (2013) The effect of various primers on shear bond strength of zirconia ceramic and resin composite. J Conserv Dent 16:499–502
26. Santos BM, Pithon MM, Ruellas AC, Sant'Anna EF (2010) Shear bond strength of brackets bonded with hydrophilic and hydrophobic bond systems under contamination. Angle Orthod 80:963–967
27. Sharma S, Tandon P, Nagar A, Singh GP, Singh A, Chugh VK (2014) A comparison of shear bond strength of orthodontic brackets bonded with four different orthodontic adhesives. J Orthod Sci 3:29–33
28. Sreedhara S, Savakkanavar MB, Rajesh Ankireddy RK, Sanajay N, Girish KS (2015) Effect of self-etch primer-adhesive and conventional adhesive systems on the shear bond strength and bond failure of orthodontic brackets: a comparative study. J Contemp Dent Pract. 16(2):130–134
29. Suh B, Schiltz M (2001) Effects of pH of single-bottle adhesive on shear bond strength. J Dent Res 80:114
30. Takamizawa T, Barkmeier W, Tsujimoto A, Scheidel D, Watanabe H, Erickson R, Latta M, Miyazaki M (2015) Influence of water storage on fatigue strength of self-etch adhesives. J Dent 43(12):1416–1427
31. Van Meerbeek B, De Munck J, Yoshida Y, Inoue S, Vargas M, Vijay P et al (2003) Buonocore memorial lecture. Adhesion to enamel and dentin: current status and future challenges. Oper Dent 28:215–235
32. Vicente A, Bravo LA (2008) Influence of an etchant and a desensitizer containing benzalkonium chloride on shear bond strength of brackets. J Adhes Dent 10:205–209
33. Yamaguchi K, Miyazaki M, Takamizawa T, Tsubota K, Rikuta A (2006) Influence of crosshead speed on micro-tensile bond strength of two-step adhesive systems. Dent Mater 22:420–425