Debonding and adhesive remnant cleanup: an *in vitro* comparison of bond quality, adhesive remnant cleanup, and orthodontic acceptance of a flash-free product

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DEDICATION

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ABSTRACT

Background: New orthodontic products are continuously introduced to clinicians seeking more practical and efficient solutions for their practice. One such product is a new flash-free adhesive for orthodontic bracket bonding, which has been introduced to the market recently. This new adhesive needs to be clinically appraised with regard to its efficacy and efficiency, and compared with conventional orthodontic adhesives that are currently in use.

Aims: To compare the quality of the bond at the enamel-bracket interface using micro-computed tomography (microCT), the amount of adhesive remaining on the tooth surface after bracket debonding, the time required for adhesive remnant cleanup, and clinical practitioners' preference between the new flash-free and a conventional adhesive.

Materials and Methods: A total of 160 bovine incisors were bonded with ceramic orthodontic brackets using the flash-free adhesive (APC Flash-Free Adhesive Coated Appliance System, 3M) on one side and a conventional adhesive (APCII Adhesive Coated Appliance System, 3M) on the other side. Twenty-four teeth were randomly selected and scanned using microCT to analyze microleakage into the adhesive layer. Twenty orthodontists debonded twenty mounted dental arches. The adhesive remnant on the bovine incisors was quantified. The orthodontists then removed the remaining adhesive. The time required for complete removal of adhesive was recorded. Finally, the orthodontists completed a specifically designed survey to evaluate their preference for one of the two adhesives.

Results: For both adhesives tested, the microleakage was very minimal with no significant differences between the two adhesives. The amount of adhesive remaining on the tooth after bracket debonding was significantly larger for the flash-free adhesive ($P<0.0001$). The adhesive cleanup was about 8% faster when using the flash-free adhesive, but the difference was not statistically significant when compared with the conventional adhesive. Fourteen out of 20 orthodontists preferred the flash-free product over the conventional product.

Conclusions: With regard to the practicality and efficiency, the new flash-free adhesive performs just as well as the conventional adhesive.

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INTRODUCTION

New orthodontic products are continuously introduced to clinicians seeking more practical and efficient solutions for their practice. One such product that strives for the title of a "practical and efficient solution" is a new flash-free adhesive for orthodontic bracket bonding, which has been introduced to the market recently.

Adhesive systems for bonding orthodontic brackets to enamel use three different agents: an enamel conditioner, a primer solution, and an adhesive resin. Phosphoric acid is the most commonly used acid for enamel conditioning before bonding. Gardner *et al*. (2001) found the quantity of good-quality etch produced by phosphoric acid at 37% was time specific, with 15 seconds being significantly less effective than 30 or 60 seconds. However, 60 seconds was not significantly better than 30 seconds (Gardner *et al*., 2001). These findings support the use of 37% phosphoric acid and suggest an optimum application time of 30 seconds.

After the completion of etching, which, if performed properly, leaves an opaque enamel surface, a resin primer is applied in a thin layer onto the etched tooth surface. The primer allows for resin tags to form in the enamel, which need to reach a sufficient depth for adequate retention. To prevent bracket failures occurring from moisture contamination, especially in the posterior region, primers with hydrophilic features are an option.

However, these hydrophilic primers have been reported to result in significantly lower bond strengths when used in a dry environment (Littlewood *et al*., 2000).

In an effort to reduce chair time, self-etching primers were introduced to reduce the bonding procedure from three to two steps by combining conditioning and priming agents into a single product. There is weak evidence indicating higher odds of failure with self-etch primer than acid etch over 12 months in orthodontic patients, and there is strong evidence that a self-etching primer is likely to result in modest time savings when compared with the conventional acid etch technique (Fleming *et al.*, 2012). Uysal *et al*. (2008) also agreed that self-etching primer causes more microleakage at enamel-adhesive interfaces, which may lead to lower bond strength and/or white spot lesions (Uysal *et al*., 2008). These findings stress the importance for practitioners to weigh the benefits of efficiency versus bond strength and the potential for weakened enamel.

After conditioning and priming, an adhesive is used to bond a bracket on the conditioned enamel surface. Most orthodontic adhesives consist of two main components; a resin phase and a reinforcing inorganic filler. The resin phase contains a modified methacrylate or acrylate. Bisphenol A diglycidyl ether methacrylate (Bis-GMA) is the most regularly used resin. It is combined with triethylene glycol dimethacrylate (TEGDMA), which influences the viscosity of the inactivated material. Fillers have an important role in determining the properties of an adhesive. Some of those properties include hardness, bond strength, surface roughness, stability, viscosity, *etc*. Regularly used fillers include several types of glass, fused silica, and quartz. There are three general types of filler irrespective of their components; macro fillers (filler particles 1-50 μm), micro fillers (filler particles 0.01-0.1 μm), and hybrid fillers (filler combination of particles 1-50 μm and submicron particles; typically 0.04 μm) fillers. Adhesives with hybrid fillers have become the adhesives of choice when bonding orthodontic brackets (Proffit, 2007).

Adhesives with higher filler contents have improved dimensional stability, increased viscosity, and increased tensile strength. Adhesives with less filler contents and therefore lower viscosity, on the other hand, might spread out and conform to the tooth surface more uniformly. Moreover, lower viscosity adhesives tend to leave more adhesive on the enamel surface after debonding (Ryou, 2008). If there is no filler present, the bond strength is reduced (Moin and Dogon, 1978).

In the course of initial bracket placement, flash, *i.e.*; excess adhesive typically flows around the bracket base onto the enamel surface as pressure is applied to the bracket. This flash needs to be removed from around the bracket base prior to adhesive cure, in order to prevent the adhesive from acting as a mechanical irritation to the gingiva, especially on teeth where the distance from the bracket pad to the gingiva is small (Eliades *et al.*, 1995). In addition, it has been demonstrated that bacteria will readily colonize the surface of rough materials such as composites, which may increase the incidence of plaque accumulation and white spot lesions (Zachrisson, 1977). Discoloration of the adhesive around the bracket is another common finding from poor excess adhesive removal.

Therefore, however time consuming the process might be, good flash removal is essential.

The development of a flash-free adhesive promises to eliminate the need to clean up flash upon bonding. The flash-free adhesive is contained within a form-fitting fiber mat on the base of the bracket. When a flash-free adhesive-coated bracket is placed on the tooth, the adhesive is designed to spread out and conform to the tooth surface, making uniform and consistent contact with no flash to clean up.

For orthodontic treatment with fixed appliances to be successful, the brackets must remain bonded to the tooth for the entire duration of treatment. A high quality bond is desired to attain such an extended period of fixation. The bond must have as little voids as possible to maintain its strength. Voids in the orthodontic adhesive may lead to bond failure, and/or plaque accumulation and subsequent formation of white spot lesions.

At the completion of orthodontic treatment with fixed appliances, the brackets are removed from the enamel surface. When a bonded bracket is removed, failure at one of three interfaces must occur: between the bonding material and the bracket, within the bonding material itself, or between the bonding material and the enamel surface. If a strong bond to the enamel has been achieved, which is the case with the modern materials, failure at the enamel surface on debonding is undesirable, because the bonding material may tear the enamel surface as it pulls away from it. The interface between the bonding material and the bracket is the failure site preferred by most orthodontists when brackets are removed (Proffit, 2007), and it is considered ideal if the adhesive remains on the tooth surface after debonding.

The amount of adhesive remaining on the enamel surface can be quantified by an Adhesive Remnant Index (Årtun and Bergland, 1984). While not absolute, the Adhesive Remnant Index (ARI) score gives a good indication of where the bond failure occurs. Obviously, the remaining adhesive needs to be removed from the tooth surface. The time spent on removal of the remaining orthodontic adhesive from the enamel surface after debonding is a large determinant of what tends to be one of the longest appointments throughout orthodontic treatment. Longer appointments require more of a patient's valuable time and are more expensive for the clinician. It would be in the best interest of both the patient and the clinician to decrease the time required for adhesive remnant cleanup. An ideal orthodontic adhesive would therefore minimize the time needed for adhesive removal.

Ease of debonding and cleanup of remnant adhesive from the enamel surface after debonding are therefore important factors for clinicians when choosing an adhesive for orthodontic bracket bonding. Little information is currently available regarding new products, such as the aforementioned flash-free adhesive. A comparison is needed of the amount of adhesive remaining on the tooth surface after bracket debonding and the removal times between this new adhesive and conventional orthodontic adhesives that are currently in use. Moreover, the acceptance of the new adhesive in the orthodontic community needs to be assessed, as the preference of clinicians will ultimately be the deciding factor for the success of a new adhesive.

AIMS

The aim of the present project was to study the efficacy of a new flash-free adhesive. More specifically, the aims were to compare (1) the quality of the bond at the enamel-bracket interface using micro-computed tomography, (2) the amount of adhesive remaining on the tooth surface after bracket debonding, (3) the time required for adhesive remnant cleanup, and (4) clinical practitioners' preference between a new flash-free and a conventional adhesive.

HYPOTHESES

The following null hypotheses were tested:

1. There is no significant difference in the quality of the bond at the enamel-bracket interface between brackets bonded with the flash-free adhesive and those bonded with a conventional adhesive.

2. There is no significant difference in the amount of adhesive remaining on the tooth surface after bracket debonding between brackets bonded with the flash-free adhesive and those bonded with a conventional adhesive.

3. There is no significant difference in time required for adhesive remnant cleanup after debonding between brackets bonded with the flash-free adhesive and those bonded with a conventional adhesive.

4. There is no significant difference in clinical practitioners' preference for the new flash-free and a conventional adhesive.

RESEARCH DESIGN AND METHODS

Specimen preparation

A total of 184 bovine incisors were collected from a local slaughterhouse, washed in running water, and stored in a 0.1% aqueous solution of thymol at room temperature (Gittner *et al*., 2010). Selection criteria included sound buccal enamel with no damage due to the extraction process. The teeth were freed from remnants of the periodontal ligament with a scalpel and the buccal enamel surfaces were flattened with an abrasive wheel (30292, Whip Mix, Louisville, KY, USA) on a dental model trimmer (Lab Master MT 15, Ray Foster Dental Equipment, Grafton, WI, USA) and pumiced using a muslin buff wheel (Buffalo Dental Manufacturing, Syosset, NY, USA) on a dental laboratory polishing lathe (Red Wing 26A, Handler Manufacturing, Westfield, NJ, USA).

One hundred and sixty teeth were mounted in self-cure orthodontic acrylic resin (Dentsply Caulk, Milford, DE, USA) in 20 sets of eight teeth; each set consisting of two central incisors and six lateral incisors to simulate a dental arch (Figure 1). The teeth were embedded in acrylic to just below the cemento-enamel junction. Care was taken to keep the buccal tooth surfaces perpendicular to the acrylic base.

Figure 1. Bovine incisors mounted in self-cure orthodontic acrylic resin to simulate a dental arch.

Each buccal tooth surface was cleaned and polished using a fluoride-free prophylaxis paste (Topex Prep&Polish, Sultan Healthcare, Hackensack, NJ, USA) on a rubber cup attached to a low-speed handpiece for 5 seconds, rinsed with water, and dried using oil and moisture-free air. Each buccal surface was etched with 35% phosphoric acid (Temrex, Freeport, NY, USA) for 30 seconds, rinsed thoroughly with water to ensure complete removal of the etchant, air-dried until it appeared dull and frosty, and primed using a light cure adhesive primer (Transbond XT Primer, 3M Unitek [3M], Monrovia, CA, USA) following the manufacturer's instructions. The teeth were then bonded with adhesive pre-coated ceramic orthodontic brackets (Clarity Advanced, 3M) using a flash-free product (APC Flash-Free Adhesive Coated Appliance System, 3M) on one side and a conventional product (APCII Adhesive Coated Appliance System, 3M) on the other side. Side allocation was randomized for each set of teeth. Two brackets were bonded to each central incisor, leaving enough room for a purpose-designed instrument to be used for debonding, while each lateral incisor was bonded with one bracket. All brackets were bonded under a constant pressure of 3 N, which was calibrated with a pressure gauge (Correx, Haag-Streit, Bern, Switzerland). Excessive adhesive around brackets bonded with the conventional product was removed with a sharp scaler. The adhesive was light-cured through the bracket for 3 seconds with a light-emitting diode polymerization device (Ortholux Luminous Curing Light, 3M). The distance between the exit window and the bracket was maintained at less than 5 mm in order to obtain adequate polymerization. After completion of the bonding procedure, the specimens were stored in distilled water at 37°C for 24 hours to allow bond maturation.

Twenty-four teeth were randomly selected from the original sample and prepared for micro-computed tomography as follows. The teeth were divided into two equal-sized groups and bonded with the flash-free product in group 1 and the conventional product in group 2 as detailed above. Two teeth, one for each product, were prepared as positive controls. These teeth had a thin adhesive tape extending between the enamel surface and the bracket base, which was removed after bracket bonding. After the bonding procedure, the teeth, with the exception of two teeth that were used as negative controls, were submerged in a 50% aqueous solution of silver nitrate (Sigma Aldrich, St. Louis, MO, USA) at room temperature for 24 hours to allow detection of microleakage into the adhesives.

Micro-computed tomography

The teeth were scanned in a micro-computed tomography system (XT H 225, Nikon Metrology, Brighton, MI, USA) at spatial resolutions ranging from 1.6 to 5 μm. The scan parameters used were 90 kV, 90 μA, 708 ms exposure time, 720 projections. Each scan projection was performed four times and then averaged to improve the signal-to-noise ratio. Three-dimensional (3-D) reconstructions of the scans were created using CT Pro 3D software (Nikon Metrology). All reconstructed images were scrutinized, slice-by-slice, for silver nitrate penetration into the adhesives, as indicated by a white line formed by the radiopaque dye between the bracket base and the enamel surface. The silver nitrate penetration was quantified using SkyScan CT-analyzer Version 1.1 (Bruker microCT, Kontich, Belgium) as follows. For each image, the adhesive layer was selected as volume of interest (VOI). Reconstructions of the VOIs were segmented to discriminate silver nitrate from background. Optimum thresholds for the segmentation of the VOIs were visually determined by gradual variation and comparison of the outcome with silver nitrate deposits on the bracket surface in the original scan (Renders *et al.*, 2006). In a segmented image, only voxels with a linear attenuation value above the threshold, *i.e.*, those representing silver nitrate, kept their original gray value, while voxels with a linear attenuation value below the threshold were made transparent. The volume of silver nitrate penetration was then calculated using the number of voxels and the scan resolution.

Debonding and adhesive remnant cleanup

Each set of teeth was mounted in a manikin head and twenty orthodontists were asked to each debond the teeth using a purpose-designed instrument (Unitek Self-Ligating Bracket Debonding Instrument, 3M) following the manufacturer's instructions (Figure 2). Each orthodontist was told that one side was "product A" while the other side was "product B". Side allocation and order of debonding were randomized for each orthodontist.

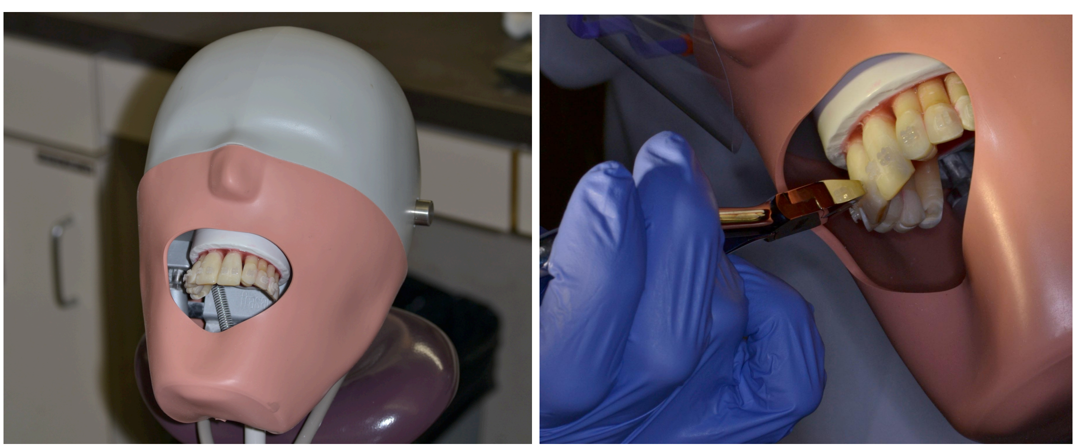

Figure 2. Debonding procedure.

Once the brackets were debonded, a single calibrated operator scored the ARI (Årtun and Bergland, 1984) under ×2.5 magnification using dental loupes (Orascoptic, Middleton, WI, USA) as follows: 0 = no adhesive left on the tooth; 1 = less than half of the adhesive left on the tooth; 2 = more than half of the adhesive left on the tooth; and 3 = all adhesive left on the tooth. Intra-operator agreement was assessed by re-scoring 5 specifically bonded and debonded arches after a washout period of 3 weeks.

The orthodontists were asked to remove the remaining adhesive from the tooth surfaces using a tungsten carbide finishing bur (H 283-21-012, Brasseler, Savannah, GA, USA) in a low-speed handpiece (David *et al*., 2002) as they would do for their patients. Adhesive removal was considered complete when the tooth surface felt smooth and appeared free of composite upon visual inspection under a dental operating light. Adhesive removal was timed to the nearest second using a digital stopwatch and verified by a single operator under ×2.5 magnification using dental loupes.

Once the adhesive remnant cleanup was completed, the orthodontists were asked to complete a specifically-designed survey aimed at determining their preference for one of the two adhesives (see Appendix). The orthodontists were also asked to rank their perceived importance of some material properties on a Likert scale. Prior to data collection, a pilot survey was conducted on 10 orthodontic staff members to test the clarity of the questions and validate the survey instrument.

Statistical analysis

Mean values, standard deviations, and coefficients of variation of the time required for adhesive remnant cleanup were calculated for each type of adhesive. Differences in adhesive removal time and silver nitrate penetration between the types of adhesives were tested for statistical significance using a paired *t*-test after the data had been tested for normality (Shapiro-Wilk test). Differences in ARI between the types of adhesives were tested for statistical significance using a Cochran-Armitage test for trend. Pearson correlation coefficients between ARI and adhesive cleanup time were calculated, separately for each type of adhesive, to evaluate the association between the ARI and the time required for adhesive remnant cleanup. Differences in the clinical practitioners debonding and adhesive removal experiences between the products were tested for statistical significance using a Cochran-Armitage test for trend. Statistical analyses were performed using SAS 9.4 for Windows (SAS Institute Inc., Cary, NC, USA). *P*-values of less than 0.05 were considered statistically significant.

RESULTS

Quality of the bond at the enamel-bracket interface

Examples of 3-D reconstructions of micro-computed tomography scans showing the area around brackets bonded with the flash-free and the conventional adhesive are shown in Figure 3. The flash-free adhesive showed a smooth, non-textured surface with the adhesive spread out, conformed to the enamel surface, making uniform and consistent contact with no flash to clean up. In contrast, the conventional adhesive showed a ruffled surface with more irregular transition from adhesive to the enamel surface, as the borders were created from removal of excess adhesive with a sharp scaler.

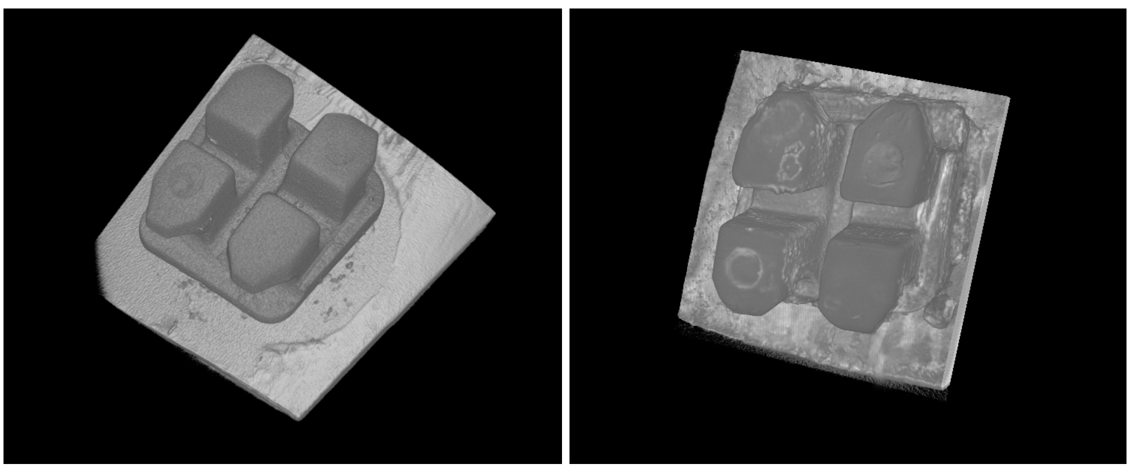

Figure 3. 3-D reconstructions of micro-computed tomography scans showing the area around brackets bonded with the flash-free (left) and the conventional adhesive (right).

Examples of micro-computed tomography scans showing a cross-section through the adhesive layer of brackets bonded with the flash-free and the conventional adhesive are shown in Figure 4. Similar to Figure 3, the flash-free adhesive showed a smooth transition from adhesive to enamel surface whereas the conventional adhesive showed a more irregular transition.

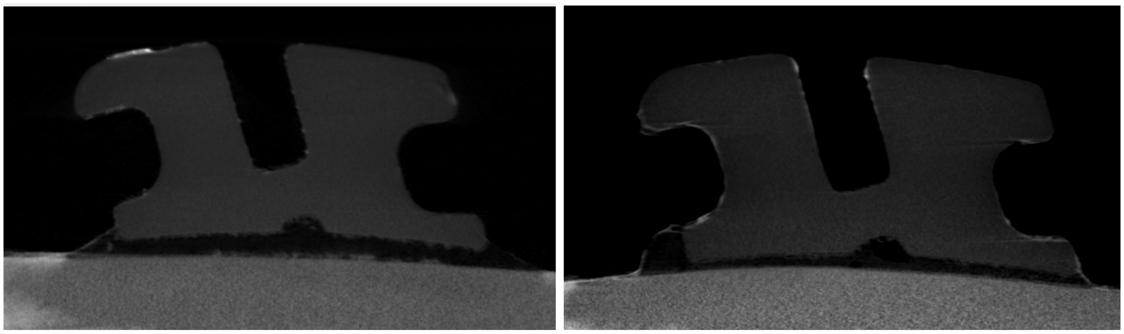

Figure 4. Micro-computed tomography scans showing the adhesive layer of brackets bonded with the flash-free (left) and the conventional adhesive (right). Radiopaque silver nitrate deposits are visible on the outer surface of the brackets, especially the gingival tie wings.

The volumes of silver nitrate penetration into the adhesives are shown in Table I. For both adhesives tested, the microleakage was very minimal with slightly more silver nitrate penetrating into the conventional adhesive. However, this difference was not found to be statistically significant (P=0.058), so the null hypothesis of no significant difference in the quality of the bond at the enamel-bracket interface between brackets bonded with the flash-free adhesive and those bonded with a conventional adhesive cannot be rejected.

Table I. Silver nitrate penetration into the adhesives.

Flash-free adhesive		*Conventional adhesive*	
Volume (mm^3)	*COV (%)*	*Volume (mm^3)*	*COV (%)*
0.000250 ± 0.000553	2.216	0.0767 ± 0.119	1.5527

Results are mean values ± standard deviations.
COV, Coefficient of variation.
No statistically significant differences between groups (Paired *t*-test, $P > 0.05$).

Amount of adhesive remaining on the tooth surface after bracket debonding

Intra-operator agreement of ARI scoring was 96%. Occurrences and percentages of ARI scores after debonding are shown in Table II. No enamel tear-outs were observed. In 94% of the brackets bonded with the flash-free product, all or most of the adhesive remained on the tooth after bracket removal indicating failure at the bracket-adhesive interface. This failure mode, as indicated by ARI scores 2 and 3, occurred in 64% of the brackets bonded with the conventional product.

Table II. Adhesive remnant index (ARI) after debonding.

	Flash-free adhesive		*Conventional adhesive*	
Score	*Occurrence*	*Percentage*	*Occurrence*	*Percentage*
0	2	2	11	11
1	4	4	25	25
2	20	20	36	36
3	74	74	28	28

0 = no adhesive left on tooth.
1 = less than half of the adhesive left on tooth.
2 = more than half of the adhesive left on tooth.
3 = all adhesive left on tooth.

The amount of adhesive remaining on the tooth after bracket debonding differed statistically significantly between the types of adhesives (P<0.0001), so the null hypothesis of no association between adhesive type and ARI is rejected.

Time required for adhesive remnant cleanup

The times required for adhesive remnant cleanup per quadrant are shown in Table III. It took on average 1:58 (min:sec) to remove the remaining adhesive of 5 brackets bonded with the flash-free adhesive while it took on average 2:14 to remove the remaining adhesive of 5 brackets bonded with APC II. On average, the adhesive cleanup was about 8% faster when using the flash-free product. However, this difference was not statistically significant (P=0.0883), so the null hypothesis of no difference in time required for adhesive remnant cleanup between the adhesives cannot be rejected.

Table III. Time required for adhesive remnant cleanup per quadrant.

Flash-free adhesive			*Conventional adhesive*		
Time (s)	*Range (s)*	*COV (%)*	*Time (s)*	*Range (s)*	*COV (%)*
118 ± 82	21 – 290	69.94	134 ± 95	30 – 351	71.00

Results are mean values ± standard deviations.
COV, Coefficient of variation.
No statistically significant differences between groups (Paired *t*-test, $P>0.05$).

After aggregating (averaging) the ARI data to the arch level, the linear association between ARI and adhesive removal time was estimated using Pearson's r, separately by type of adhesive. For the conventional adhesive the correlation was fairly high (r=0.52068) and statistically significant (P=0.0186), whereas for the flash-free adhesive it was lower (r=0.07675) and not statistically significant (P=0.7477). The restricted ARI range in the flash-free adhesive group (no value lower than 1.8) is the main reason why the correlation coefficient was low.

Clinical practitioners' preference

Eighty percent of clinicians rated their debonding experience with the flash-free product as "somewhat pleasant" or "very pleasant" while 60 percent of clinicians rated their debonding experience with the conventional product as "somewhat pleasant" or "very pleasant". Although the frequency distribution involved more positive ratings for the flash-free adhesive than for the conventional adhesive, the difference was not statistically significant (P=0.1792).

Seventy-five percent of clinicians rated their adhesive removal experience with the flash-free product as "somewhat pleasant" or "very pleasant" while 50 percent of clinicians rated their adhesive removal experience with the conventional product as "somewhat pleasant" or "very pleasant". Although the frequency distribution involved more positive ratings for the flash-free adhesive than for the conventional adhesive, the difference was not statistically significant (P=0.1538). Fourteen out of 20 orthodontists preferred the flash-free product over the conventional product for the following reasons (more than one reason per clinician possible):

- Easier to remove (8)
- Less force needed for bracket debonding (4)
- Softer material (3)
- Faster to remove (2)
- Less pressure needed on handpiece for adhesive removal (2)

- Easier to see (1)
- More predictable debonding (1)

The other six orthodontists preferred the conventional product over the flash-free product for the following reasons (more than one reason per clinician possible):

- Less adhesive remaining on tooth (4)
- Easier to remove (2)
- Faster to remove (1)

Occurrences and percentages of clinical practitioners' perceived importance Likert scores of some material properties are shown in Table IV.

Table IV. Perceived importance of material properties.

	Amount of adhesive remnant		*Time for adhesive remnant cleanup*		*Ease of adhesive remnant cleanup*		*No need for polishing*	
Importance	*Occ*	*%*	*Occ*	*%*	*Occ*	*%*	*Occ*	*%*
Unimportant	1	5	0	0	0	0	1	5
Of little importance	4	20	2	10	1	5	4	21
Moderately important	6	30	4	20	4	20	3	16
Important	6	30	3	15	3	15	7	37
Very important	3	15	11	55	12	60	4	21

Occ, Occurance.
%, Percentage

The majority of orthodontists considered the time required for adhesive remnant cleanup and ease of adhesive remnant cleanup “very important” (55% and 60%, respectively), while the amount of adhesive remaining on the tooth surface after debonding and the absence of a need for polishing were felt to be of less importance.

DISCUSSION

The ideal adhesive for orthodontic bracket bonding should have a high quality bond at the enamel-bracket interface and should remain attached to the enamel surface after debond, limiting the probability of enamel tear-outs. It would be an added benefit if the adhesive remnant left behind required very little time to cleanup. This study set out to examine a new flash-free adhesive and determine if it should be labeled as a practical and efficient solution.

Quality of the bond at the enamel-bracket interface

In dentistry, microleakage is defined as seeping and leaking of fluids and bacteria between the enamel-composite interface (Gladwin, 2004). For operative dentistry, it has been shown that microleakage increases the likelihood of recurrent caries and postoperative sensitivity (Gladwin, 2004). From an orthodontic perspective, it has been shown that microleakage around orthodontic brackets can be a cause for the formation of white spot lesions (James, 2003). Thus, the investigation of microleakage between bracket-adhesive interfaces is of importance for the clinical success of treatments and bonding orthodontic brackets.

Using micro-computed tomography, it was found that both the flash-free and the conventional adhesive show a very high quality of the bond with very minimal microleakage at the enamel-bracket interface. The null hypothesis, that there is no significant difference in the quality of the bond at the enamel-bracket interface between brackets bonded with the flash-free adhesive and those bonded with a conventional adhesive is well supported by the present results. These findings are in agreement with an earlier study that has shown that little or no microleakage is observed between the adhesive-enamel interfaces when using 3M's Transbond-XT adhesive (Uysal, 2009), which is the adhesive used in the APC II Adhesive Coated Appliance System used as the control in the present study.

Amount of adhesive remaining on the tooth surface after bracket debonding

In the present study, the flash-free adhesive failed more reliably and predictably at the bracket-adhesive interface or, more likely, the bracket-mesh interface. This bracket-mesh interface is of a new design in the flash-free product compared to the conventional product. Although the exact design and mechanism of fracture is trade secret, we hypothesize that fracture is more likely at the bracket-mesh interface due to lower bracket density at the site.

Upon bracket removal, the flash-free adhesive left more adhesive on the tooth surface after debond than the conventional adhesive. These results did not support the null hypothesis that there is no significant difference in the amount of adhesive remaining on the tooth surface after bracket debonding between brackets bonded with the flash-free adhesive and those bonded with a conventional adhesive. In 94% of the brackets bonded with the flash-free product, all or most of the adhesive remained on the tooth after bracket removal, while that was the case in only 64% of the brackets bonded with the conventional product. Although, to our knowledge, ARI analysis has not been completed on the flash-free adhesive in other studies, very similar findings have been reported for the conventional adhesive used in this study: A recent study showed the majority of ARI scores being either 2 or 3 (Sharma, 2014). The findings of the present study suggest that typically more adhesive is left on the enamel surface after debonding when using the flash-free adhesive. This is beneficial to orthodontic patients as it minimizes the risk of enamel tear-outs. However, more material remains on the tooth surface, which requires cleanup.

Time required for adhesive remnant cleanup

The remaining adhesive was cleaned off faster when using the flash-free product, despite there being more adhesive to cleanup. Although the differences were not statistically significant and the present results support the null hypothesis that there is no significant difference in time required for adhesive remnant cleanup after debonding between brackets bonded with the flash-free adhesive and those bonded with a conventional adhesive, removal of the flash-free adhesive was on average, 8% faster than the conventional adhesive. The absence of statistically significant differences is most likely a consequence of the rather large standard deviation. While some orthodontists removed the adhesive in less than 30 seconds, it took others about 5 minutes. This result, at first glance, might appear surprising, because the flash-free adhesive left more adhesive on the enamel surface after bracket debonding than the conventional adhesive. We believe that the softer consistency of the flash-free adhesive played a role in the ease of removal. The softer consistency is likely due to the flash-free adhesive's lower viscosity and lower filler content when compared with the conventional adhesive. The resulting decrease in time for removal of the flash-free adhesive can be considered beneficial to both practitioners and patients as use of the flash-free adhesive may result in less chair time.

Although no studies are currently available on the bond strength of the flash-free adhesive used in this study, several studies compared the bond strength of the conventional adhesive used in the present study to more flowable, less filled adhesives (Uysal, 2004; Gama, 2013). One study found 3M's Transbond XT adhesive to have higher flexural modulus and shear bond strength (SBS) and lower contraction stress than the more flowable adhesives it was compared with (Gama, 2013). Another study demonstrated that the Transbond XT adhesive had higher SBS values than the less-filled composites; and interestingly, significantly more adhesive remained on the enamel surface with the less-filled adhesives compared to the Transbond XT (Uysal, 2004). These findings are similar to the present results and support our idea that the flash-free adhesive is less filled than the conventional adhesive. The softer consistency of the flash-free adhesive should lead to ease of bracket debonding and adhesive remnant cleanup, possibly adding to a more positive experience for the clinical practitioner.

Clinical practitioners' preference

In the setting used in this study, the majority of orthodontists preferred the flash-free product over the conventional product because of force needed for bracket debonding and the speed of adhesive remnant removal. Although we found more positive ratings for the flash-free adhesive than for the conventional adhesive, the results support the null hypothesis that there is no significant difference in clinical practitioners' preference for the new flash-free and the conventional adhesive. Interestingly, four practitioners, who preferred the conventional adhesive when removing adhesive, stated that their decision was based on the lower amount of adhesive remaining on the enamel surface after debonding. It is assumed that these practitioners may not have been aware of the increase in likelihood of enamel tear-outs with less adhesive remaining on the enamel surface (Proffit, 2007), or considered a decrease in adhesive removal time to be worth the higher risk of enamel tear-outs.

Based on our findings, clinical practitioners seem to prefer an adhesive material that is easy to debond and can be removed from the enamel surface quickly and easily after debonding. A softer, less filled adhesive makes for easier debonding and faster cleanup. In contrast, a harder, more filled adhesive may have increased SBS, which may result in fewer bond failures during treatment. Future studies should examine the SBS of the flash-free adhesive to determine if it is adequate for orthodontic treatment with the added benefits of being easy to debond and quick to remove from the tooth surface.

Methodological considerations

Non-human dental tissues are commonly used within dentistry as models for the study of material properties. The present work used bovine teeth as a model for human teeth. Previous studies have found no significant difference in bond strength between human and bovine enamel (Krifka *et al*., 2008). Although bovine incisors correspond remarkably well to human teeth (Nakamichi, 1983), there is no guarantee that the results found in this study can be reproduced in humans. Future *in vivo* studies comparing the flash-free adhesive to conventional products would help to determine if an accurate correlation exists between bovine incisors and human teeth.

The adhesive removal and clinicians preference portion of this study was conducted at the University of Minnesota with alumni, part-time, or full-time faculty members of the Graduate Program in Orthodontics at the University of Minnesota performing the tasks. Not all of these individuals routinely remove adhesive using a slow-speed handpiece in their practices. This may have affected both differences in time of adhesive removal and clinical preference. Furthermore, adhesive removal techniques vary from state to state based on laws regulating the use of certain instruments. Finally, a clinician's preference may be influenced by the standard operating procedure in their practice, *i.e.* orthodontists' removal themselves versus assistant removal of adhesives.

Future studies

A study of the clinical application of the flash-free adhesive *in vivo* is the next logical progression in the evidence-based research. This *in vivo* study should be directed at bonding time and bond survival in addition to the parameters evaluated in the present study. A chemical analysis could evaluate the different chemical make-ups of the two types of adhesives, which might result in a better understanding of why the flash-free adhesive was removed faster than the conventional adhesive. A closer examination of the design details of the bracket-mesh interface might also help explain the more consistent location of bond failure of the flash-free product during debonding.

CONCLUSIONS

1. Both the flash-free and the conventional adhesive show a very high quality of the bond with very minimal microleakage at the enamel-bracket interface.

2. The flash-free adhesive fails more reliably and predictably at the bracket-adhesive interface, which is considered the preferred failure mode by most orthodontists as it minimizes the risk of enamel tear-outs.

3. There is no statistically significant difference in adhesive remnant removal time between the flash-free and conventional adhesives. However, there is a trend toward faster cleanup when using the flash-free product, despite a larger amount of adhesive remaining on the tooth after bracket debonding, which may be of clinical relevance.

4. The majority of orthodontists prefer the flash-free product over the conventional product because it is easier and faster to remove, and less force is needed for bracket debonding and adhesive removal.

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APPENDIX

Debonding and adhesive remnant cleanup: an *in vitro* study of bond quality, adhesive remnant cleanup, and acceptance of a new product for orthodontic bracket bonding

Please take a few minutes to fill out this survey on your recent debonding and adhesive remnant cleanup experience with two products for orthodontic bracket bonding. Your responses are anonymous and not answering any question on the survey will not affect your relationship with the University of Minnesota.

Thank you. Completion of the survey implies informed consent.

1. How would you describe your experience of debonding brackets bonded with product A?

O	O	O	O	O
Very unpleasant	Somewhat unpleasant	Neutral	Somewhat pleasant	Very pleasant

2. How would you describe your experience of adhesive remnant cleanup with product A?

O	O	O	O	O
Very unpleasant	Somewhat unpleasant	Neutral	Somewhat pleasant	Very pleasant

3. How would you describe your experience of debonding brackets bonded with product B?

O	O	O	O	O
Very unpleasant	Somewhat unpleasant	Neutral	Somewhat pleasant	Very pleasant

4. How would you describe your experience of adhesive remnant cleanup with product B?

O	O	O	O	O
Very unpleasant	Somewhat unpleasant	Neutral	Somewhat pleasant	Very pleasant

5. If you had to choose an adhesive for orthodontic bracket bonding solely on your debonding and adhesive remnant cleanup experience, which product would you prefer?

- ○ Product A
- ○ Product B

Why?

____

____

6. Is there anything in particular that you liked or disliked about product A?

I liked:

____

____

____

I disliked:

____

____

____

7. Is there anything in particular that you liked or disliked about product B?

I liked:

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____

____

I disliked:

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____

____

8. How important are the following properties to you when selecting an adhesive for orthodontic bracket bonding?

Amount of adhesive remaining on the tooth surface after bracket debonding

○	○	○	○	○
Very important	Important	Moderately important	Of little importance	Unimportant

Time required for adhesive remnant cleanup

○	○	○	○	○
Very important	Important	Moderately important	Of little importance	Unimportant

Ease of adhesive remnant cleanup

○	○	○	○	○
Very important	Important	Moderately important	Of little importance	Unimportant

No need for polishing after adhesive remnant cleanup

○	○	○	○	○
Very important	Important	Moderately important	Of little importance	Unimportant