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Title

The influence of enamel sandblasting on the shear bond strength and fractography of the bracket-adhesive-enamel complex *tested in-vitro by the DIN 13990:2017-04-standard*

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Abstract

Objectives: To investigate by the DIN 13990:2017-04-standard, whether enamel sandblasting as an adjunct or substitute to the acid-etch technique has an effect on the shear bond strength (SBS) and fractography of the bracket-adhesive-enamel complex.

Materials and Methods: Upper central incisor brackets (discovery®, Dentaurum, Germany) were bonded using Transbond XT™ (3M Unitek, Germany) on bovine incisors prepared by four different methods (15 samples each): sandblasting with 27 µm Al_2O_3 at 1.2 bar (s), acid etching with 37.4 % phosphoric acid (a), sandblasting with 27 µm Al_2O_3 at 1.2 bar followed by acid etching (s1a) and sandblasting with 50 µm Al_2O_3 at 5.7 bar followed by acid etching (s2a). The SBS and Adhesive-Remnant-Index (ARI) were measured, followed by one-way analysis of variance and Fisher's exact tests at 5%.

Results: The SBS in the groups s (5.6±2.2 MPa), a (17.1±4.3 MPa), s1a (18.3±4.3 MPa) and s2a (18.5±4.6 MPa) indicated that the s group was significantly inferior to all other groups ($p<0.001$). Likewise, the ARI analysis indicated different performance of the s group (mostly ARI of 0) compared to the other groups ($P<0.001$) and a tendency for different ARI between the a and s1a/s2a groups.

Conclusions: In-vitro enamel sandblasting could not substitute acid etching and did not offer improved SBS when used before acid etching, regardless of air pressure and powder granulation. Sandblasting without acid etching produced less residual resin on the tooth after debonding.

Clinical Relevance: The clinical use of adjunct enamel sandblasting prior to etching to enhance SBS has to be questioned.

Keywords: shear bond strength; SBS; sandblasting; DIN 13990; lingual orthodontics; bracket

Introduction

Background

Although bonding brackets to teeth with composite resins has been a common procedure in orthodontics for many decades, bond failure during treatment is a frequently encountered problem and has a negative impact on the orthodontic treatment, such as increased chair time for the re-bond or prolonged overall treatment duration [1]. Failure of lingual brackets may have an even higher negative impact on clinical practice compared to labial appliances, because of the reduced field of view and the prefabricated individualized materials used. In lingual orthodontics, in the early years, clinicians were faced with high bonding failure rates, which were counterbalanced at least in part by developing individualized precise matching bracket bases and new bonding protocols, like indirect bonding and enamel sandblasting prior to etching, leading to comparable bond performance [2].

Enamel sandblasting is widely used as an adjunct to the traditional acid-etch technique, even though its effect on Shear Bond Strength (SBS) and the clinical failure rate are controversial. In vitro comparative studies on sandblasting prior to acid etching vs. acid etching alone revealed variable results. The bond strength was improved by 42 % when testing brackets bonded on labial surfaces of extracted human premolars in a tensile mode [3], by 34 % when using composite cylinders bonded to bovine teeth [4], by 25 % when using lingual brackets bonded indirectly on extracted human premolars [5], and by 10 % when testing brackets bonded on fluorosed enamel of extracted human premolars [6]. Testing of different retainer wires and bonding adhesives on bovine teeth showed increased mean SBS by 217 % for specimens bonded on sandblasted enamel [7]. Other in vitro studies – all conducted with human premolars – revealed no difference in SBS of the enamel-adhesive-bracket complex after adjunct enamel sandblasting compared to no sandblasting [8–12], even after using different powder's particle size [12]. In one study it was shown that enamel sandblasting before using a self-etching primer increased significantly the SBS on the buccal surfaces of extracted premolars, but the increase found on the lingual surfaces was not statistically significant [13]. Other researchers indicated that gains in terms of bond strength of metal brackets bonded on buccal surfaces of extracted human premolars using a self-etching primer were dependent on the sandblasting powder's particle size – i.e. no difference was found when using 25 µm aluminium oxide (Al_2O_3) powder, but increased SBS by 21 % and 41 % resulted from using 50 µm and 100 µm Al_2O_3 powders, respectively [14]. On the other hand, in vitro studies comparing enamel sandblasting alone to traditional enamel etching showed a uniform inferiority of the former (in terms of 39-78 % reduction in SBS), indicating that enamel sandblasting cannot substitute acid etching [3, 10, 15, 16].

Clinical failure rates of brackets bonded on the buccal side of non-sandblasted teeth with a conventional two-step etch and primer method over the period of one year have been reported from many in vivo studies to vary between 1.7 % and 11.0 % [2, 17–21]. In the only study reporting on the clinical failure rate of brackets bonded lingually on sandblasted enamel, the failure rate was found to be 10 % for lingual (with enamel sandblasting) and 11% for buccal (without enamel sandblasting) brackets within the first year after bonding [2]. There is to our knowledge no prospective clinical trial directly assessing the failure rate of bonded brackets in conjunction with enamel sandblasting.

Sandblasting might also be associated with detrimental effects and has been shown to alter significantly the enamel surface microscopically, which becomes rougher, loses greater amounts of enamel, and exhibits the same extent but improved quality of resin infiltration after adjunct sandblasting followed by acid-etching compared to acid etching alone [22]. Enamel sandblasting is known to damage the surface of the tooth, even though, post-debond polishing of the teeth is considered to reconstitute the enamel's surface properties, at least in part. Additionally, enamel sandblasting might lead to gingiva injury, causing bleeding, and thereby complicating the bonding process. Finally, sandblasting is time-consuming and potentially unpleasant for both the patient and the orthodontist. Despite the fact that the sand can be thoroughly disposed of with a rubber dam and suction [23], part of it is spread around the treatment room and might be inhaled by patients and treating staff, though with no obvious potential pulmonary risk [24].

Currently, there is no consensus on orthodontic bond strength protocols, with great heterogeneity across or within various research teams. For that reason, the DIN-13990-2:2009-05-standard [25] was introduced in 2009, updated in 2017 to the DIN 13990:2017-04 [26], and since then has been widely implemented [27–33]. Despite its widespread use, the effect of enamel sandblasting has not yet been tested by the DIN standard.

Objectives

Therefore, the purpose of this study was to investigate, whether enamel sandblasting as an adjunct or substitute to the acid-etch technique has an effect on the bond strength of the bracket-adhesive-enamel complex when tested according to the DIN 13990:2017-04-standard. Furthermore, we evaluated the influence of enamel sandblasting on bracket fractography, i.e. the distribution of residual adhesive on the enamel after shear testing.

Materials and Methods

Specimen preparation

Bovine lower front teeth of animals between two and five years old were extracted and disinfected with the neutral formaldehyde containing, Calgonit Sterizid Form (Calvatis GmbH, Ladenburg, Germany) in the slaughterhouse. The teeth were acquired by a local supplier (Rocholl GmbH, Aglasterhausen, Germany), who disinfected them with the formic acid containing VENNO® VET 1 super (MENNO CHEMIE-VERTRIEB GMBH, Norderstedt, Germany) for two hours, removed the gingiva, nerve and root and cleaned them under clear water. The teeth were stored in tap water and were shipped to our laboratory in wet conditions.

Further specimen preparation was conducted according to DIN 13990:2017-04. After receipt, the teeth were disinfected for one week in bacteriostatic 0.5 % Chloramine T-solution (Chloramine T Sodium Salt Trihydrate, MP Biomedicals Germany GmbH, Eschwege, Germany) at room temperature, i.e. 23 (±2) °C and afterwards stored in 4 (±2) °C cold ultrapure water, DIN ISO 3696, Quality 3 (Ampuwa®, Fresenius Kabi Deutschland GmbH, Bad Homburg, Germany). Teeth with significant enamel grooves or defects, de-mineralisations, fractures or caries were excluded. The surface to be bonded had to be flat and minimum twice as big as the bracket itself. The teeth were embedded in cylindrical resin bases made of Technovit® 4004 (Kulzer GmbH, Hanau, Germany) and the buccal enamel surface was cleaned with pumice stone and a cloth polishing brush before bonding. During the whole preparation process, the teeth did not become dry, while all tests were performed within the first 6 months after extraction.

We conducted a sample size analysis using the software G*Power 3.1.9.2 [34], based on a previous study: The bond strength of composite cylinders bonded on bovine teeth was improved by 34.3 % on average by sandblasting before acid etching the enamel (32.5 MPa, SD=4.88, n=20) vs. acid etching alone (24.2 MPa, SD=6.16, n=20), showing an effect size of f=0.745 [4]. We chose this study because the bond strength for the non-sandblasted acid etched teeth matched best with previous results from our laboratory [28]. Calculation of sample size, based on the ability to detect a difference in shear strength of 34.3 % between the three acid etching groups (100 % vs. 134.3 %) with $\alpha = 0.05$ and power $1-\beta = 0.80$ revealed a total sample size of 21 (7 per group). A minimum of 10 samples is required according to the DIN 13990:2017-

04-standard. The sample size was set to 15 per group to increase the power. We did not consider sandblasting-only for the sample size calculation.

We implemented four different enamel preparation protocols: the enamel was either solely sandblasted (s) or solely acid etched (a) or initially sandblasted with two different sandblasting methods and subsequently acid etched (s1a, s2a) (Table 1). For each method, 15 randomly chosen specimens were prepared. Sandblasting was performed by hand for four seconds under constant movement: For groups s and s1a, a MicroEtcher CD (Fig. 1, Danville Materials, San Ramon, California, USA) was attached to the turbine hose of the dental unit, i.e. after air pressure reduction, and the foot pedal was adjusted at the lowest possible air pressure at 1.2 (±0.2) bar for sandblasting with 27 µm Al_2O_3. For group s2a, a MicroEtcher IIA (Fig. 1, Danville Materials, San Ramon, California, USA) was attached to a pressure hose before the dental unit, i.e. without any pressure reduction, and delivered an air pressure of 5.7 bar for sandblasting with 50 µm Al_2O_3.

After sandblasting, 37.4 % phosphoric acid gel (gel in bottle REF 163-415-00, Dentaurum) was applied to the specimens of groups a, s1a and s2a for 15 seconds and was washed off with water for another 15 seconds; then the enamel was air-dried with oil-free pressurized air.

Upper right central incisor brackets (discovery®, Dentaurum J. P. Winkelstroeter KG, Pforzheim, Germany) with laser structured bases (surface: 12.12 mm²) were bonded on the bovine incisors with a light-curing adhesive system (Transbond XT™, 3M Unitek, Landsberg, Germany), after being degreased with 96 % alcohol (Fig 2a). The bracket bases were flat, to achieve a uniform adhesive layer thickness as proposed in the DIN 13990:2017-04-standard. A thin film of primer was applied on the pre-treated enamel surface and the base of the bracket was covered with an even layer of adhesive. The brackets were pressed manually on the tooth and the uncured primer and excessive adhesive were carefully removed by a dental explorer and a brush. The primer and the adhesive were cured once with a halogen polymerisation lamp (PolyLUX II, KaVo Dental GmbH, Biberach, Germany) by hand from each side (mesial and distal) for 10 seconds at 5 mm distance over the bracket in a 30° angle to the bonded surface. After bonding, all specimens were stored in 37 (±2) °C Ampuwa® (Fresenius Kabi Deutschland GmbH, Bad Homburg, Germany) for 24 (±2) hours until bond strength testing began at room temperature.

Shear bond strength testing

The specimens were tested with the material testing machine ZMART.PRO® (Zwick GmbH & Co. KG, Ulm, Germany) according to the DIN 13990:2017-04-standard (Fig. 2b). The adhesive zone between tooth and bracket was positioned parallel to the applied force. The specimens were positioned so that the force was applied from the occlusal to the gingival direction of the bracket. A stainless steel blade with a thickness of 0.5 (±0.05) mm and a square-cut aperture of the side length of 6.0 (±1.0) mm was placed around the bracket exactly onto the bracket base and was used as a force transduction device; the blade was held by hand during loading to assure correct position. This way we guaranteed that no rotational moment was applied on the brackets, which could have resulted into a more tensile fracture mode as when applying the force on the bracket body or wings. The testing machine was controlled by a personal computer with the software testXpert® II (Zwick GmbH & Co. KG, Ulm, Germany). The shear strength test was conducted with a constant speed of 1 mm/min until the compound broke. A load-displacement diagram was drawn for every test body. The fracture force was defined as the last measured value before the curve fell more than 30 %.

Fractography

All tooth surfaces were examined and photographed under 12x magnification with an optical microscope with an external light source and appropriate software (Stereo Wild MZ 7.5 / KL 2500 LCD / Leica Application Suite V 4.10 – LAS Core, Leica Microsystems GmbH, Wetzlar, Germany) with a resolution of 2592 x 1944 Pixel. They were positioned in a standardized way, perpendicular to the viewing light beam to avoid distortion. The area of the bracket base (as distinguished from the edges of the residual adhesive on the enamel) and the area of any remaining adhesive within the bracket base area were subjectively traced for each specimen with the help of the software ImageJ (Java®, Sun Microsystems, Inc., Santa Clara, California, USA). The pixel numbers of the adhesive-covered area in relation to the bracket base area were converted into percentage values and transformed into the Adhesive-Remnant-Index (ARI) [35] according to the target values given in Fig. 3, in order to express the – otherwise subjective – index in a more reproducible way.

In an additional visual analysis of the enamel surfaces, we classified the fracture mode of each specimen in: adhesive (fracture between the adhesive and the adherent - the resin remained entirely on the enamel or the bracket base), cohesive (fracture within the adhesive layer resulting in adhesive remains on both the enamel and the bracket base) or mixed (partly adhesive and party cohesive fracture mode).

Statistical analysis

We conducted descriptive and inferential statistics using IBM SPSS Statistics 23 (IBM Corporation, New York, USA). The dependence of shear strength from the enamel preparation protocol was analysed by one-way analysis of variance (ANOVA) after checking for normality of residuals and homogeneity of variances (α=5%) followed by post hoc pairwise comparisons with Sidak p-value correction [36]. We analysed the fractography patterns resulting from the enamel preparation protocols applying Fisher's exact test, as 50-75 % of the expected frequencies were less than five. For all tests, the significance level was set at a two-sided P value of 0.05.

Results

The measured shear forces at failure and SBS values of tested samples are presented in Table 2a and Fig. 4. Considerable variation in SBS became obvious, with the enamel preparation protocol being a significant influencing factor (Table 2b; $p<0.001$). The Sidak post hoc pairwise comparisons (Table 2c) indicated that significant differences existed between the sandblasting-only group and all others, with the sandblasting-only group having reduced SBS values by 67-69 % compared to all acid-etching groups ($p<0.001$). No statistically significant differences were found between the acid etching group and the two combined sand-blasting and acid etching groups. Thus, sandblasting prior to acid etching did not increase the SBS compared to acid etching alone. Likewise, the specific method of sandblasting, i.e. pressure and particle size, did not influence the results, as there was no statistically significant difference between the two combined sandblasting and acid etching groups.

The results of the fractography analysis are presented in Table 3 and Fig. 5. Overall, 63 % of the specimens showed ARI 1 and no enamel fractures (ARI 4) were found. In the sandblasting-only group, 80% of the specimens showed ARI 0 and 20 % ARI 1, indicating that no or little adhesive remained on the tooth. In the etching-only group, 60% showed ARI 1, 33% ARI 2 and 7% ARI 3. In the sandblasting and etching groups, 0-7% showed ARI 0, 80-93 % ARI 1 and 7-13% ARI 2. Fisher's Exact Test showed a significant influence of the enamel preparation protocol on the ARI ($p<0.001$). On the other hand, after excluding the s group that obviously differed from the other three groups, group a tended to have different ARI distribution, with more ARI values of 2 or 3, compared to groups s1a/s2a. However, this was not statistically significant ($p=0.13$) when tested with an additional Fisher's exact test in a post hoc explorative comparison, probably due to low power. A further Fisher's exact test between s1a and s2a indicated no significant difference between the two sandblasting and etching groups (p=0.60).

The additional visual analysis (Table 4a) showed that 82 % of all specimens presented an adhesive and no specimen a cohesive fracture mode. 18 % of the specimens showed a mixed fracture mode, all of them showing also ARI 1, representing 29 % of all ARI 1 specimens (Table 4b). Fisher's Exact Test showed no significant influence of the enamel preparation method on the fracture mode (p=1.0) and a significant correlation between ARI and fracture mode (p=0.038).

Discussion

Enamel sandblasting is widely used in orthodontics as a means to enhance bond strength and reduce bracket failure rate, especially in the lingual technique. It is also recommended for cleaning the enamel before bonding lingual brackets or retainers. However, its effectiveness on SBS remains questionable, since contradicting results exist. Thus, the purpose of the present study was to replicate the results of previous studies on this topic using a robust experimental protocol for SBS testing. The DIN 13990:2017-04-standard was established to unify the heterogeneous SBS testing methods that might contribute to the existence of different results across researchers. This standard delineates every detail of the experimental setup from tooth selection and specimen preparation to mechanical testing, while only a few points are left to the flexibility of the researcher, such as the use of bovine instead of human teeth. Consequently, the standardized methodology allows for good independent replication of study results in the future – a task that is of paramount importance in the scientific process.

To our knowledge, this is the first study to assess the effect of enamel sandblasting on SBS according to the DIN 13990:2017-04-standard.

Our results conform with previous studies analysing SBS after sandblasting-only vs. acid etching: 67 % reduction of SBS compared to 58-78 % reduction in other studies [10, 15, 16]. Therefore, it seems that sandblasting alone cannot substitute the acid etching technique for bonding orthodontic attachments.

Our results about the effect of adjunct sandblasting prior to acid etching, showing that no significant improvement in SBS compared to acid etching alone is seen, are conform with most of the existing studies [8–12]. In all of these studies, human premolars were used, while one study implemented indirect bonding of lingual brackets on lingual tooth surfaces after using sandblasting with different powder's particle size [12].

On the other hand, the results of studies indicating increased SBS by sandblasting on human [5] or bovine teeth [4] using simulated indirect bonding could not be confirmed. This might be attributed to differences in the bonding procedure, causing an altered structure of the enamel-adhesive-bracket interface compared to direct bonding (i.e. the existence of an extra resin layer, of different resins, and of different layer thickness). The reported improvement in tensile bond strength in combination with sandblasting [3] is not comparable to our study since we tested especially shear bond strength. Finally, data indicating a sandblasting-induced improvement of SBS when testing brackets bonded on the fluorosed enamel of extracted human premolars [6] is not comparable to our study, since brackets were bonded on intact enamel. The data showing highly improved SBS for different retainer wires and bonding adhesives on bovine teeth for specimens bonded on sandblasted enamel [7] are not comparable to our study since a totally different methodology was used.

The effect of varying sandblasting particles was likewise found to be of minimal importance as far as SBS is concerned. This is in accordance with previous data indicating no difference in SBS after acid etching alone or adjunct sandblasting with 27, 50, and 90 µm Al_2O_3 [12] and in part with a study showing similar SBS after acid etching alone and adjunct sandblasting with 25 µm Al_2O_3 (but increased SBS when using higher particle sizes) [14].

It is important to note that SBS values measured intraorally after comprehensive orthodontic treatment are considerably lower than those measured by in vitro protocols – being on average 57% lower than in vitro SBS values (5.5 MPa and 12.8 MPa, respectively) [37]. Also, in vitro strength values after cyclic fatigue are on average 41-77% lower than the ultimate shear strength [28]. In addition, the mode of the intraorally applied force is different from the in vitro DIN 13990:2017-04-standard, whereas the latter relies on a theoretical approach to facilitate a reproducible protocol. Contrary to that, the debonding forces applied in vivo are more likely to be applied on the bracket wings than on the bracket base, thus creating more rotational and tensile forces. Therefore, the clinically necessary force for bracket debonding is expected to be smaller than those measured in our study.

The mean occlusal forces during chewing and maximum biting of children have been reported at 38 N – 92 N and 103 N – 171 N respectively [38]. The mean occlusal forces during chewing and maximum biting of adults have been reported at 41 N – 159 N and 110 N – 349 N respectively [39]. Assuming that the clinically necessary force for bracket debonding would be reduced by 57 % [37] than those measured in our study, the method of sandblasting only (43% x 68 N = 29 N, eq. to 2.4 MPa) would probably not even withstand chewing occlusal forces of children or adults. The methods of acid etching (43 % x 207 N = 89 N eq. to 7.3 MPa) or sandblasting and acid etching (43 % x av. 222.5 N = 96 N eq. to 7.9 MPa) would probably endure almost all children chewing forces, some chewing forces of adults and definitely fail with children or adult maximum biting forces. However, these are theoretical indirect extrapolations that have not been directly tested experimentally and should be viewed with caution.

Utilization of bovine teeth is explicitly permitted according to the DIN 13990:2017-04-standard. Bovine teeth are commonly used in dental research instead of human teeth because they are accessed easily and are available in large quantities. Their use as a substitute for debonding testing purposes is a matter of dispute [40, 41]. In a systematic review [40] it was reported that 10 of 17 SBS studies showed comparable results in tests with human and bovine teeth, whereas seven studies revealed lower SBS values for bovine teeth. Thus, the reader should expect similar or higher values to ours if conducting the same experiment with human teeth.

There is wide consensus, that after debonding ideally as much as possible adhesive should remain on the tooth, in order to reduce the risk of enamel fracture. We showed that sandblasting before etching reduces the chances for more than 50 % (ARI 2: 7-13 % vs. 33 %) or all adhesive (ARI 3: 0 % vs. 7 %) left on the tooth and it is more likely to produce less than 50 % residual adhesive on the tooth after debonding (ARI 1: 80-93 % vs. 60 %) compared to etching-only; however, this was not statistically significant (p=0.13), probably due to low power. Given the similarly high bond strength in both cases (17.1 – 18.5 MPa), which might exceed the ultimate tensile strength of human enamel (11.7 – 47.5 MPa) depending on the prismatic orientation in relation to the applied force [42, 43], adjunct sandblasting might be associated with increased enamel fracture risk compared to etching-only. However, it should be noted that no enamel fractures were observed in this experiment. In the sandblasting-only group, 80 % of the specimens showed no remaining adhesive on the tooth (ARI 0), indicating a very weak enamel-adhesive interface supported by the significantly reduced overall SBS. The two sandblasting and etching groups showed statistically similar ARI distribution, indicating that air pressure and powder granulation did not influence the fractography results.

Nevertheless, less adhesive remaining on the tooth means less burden for the clinician to remove the remnants from the tooth surface. Considering the individualized resin bracket bases in some lingual systems, a persistent intact resin bracket base may facilitate accurate placement of the brackets in case of necessary rebonding. In this aspect, sandblasting before acid etching can be considered advantageous compared with acid etching alone.

The visual fracture mode analysis (Tables 4a & 4b) showed adhesive fractures for the majority (82 %) of all specimens. The different enamel preparation methods showed no difference in the distribution of the fracture modes (Table 4a). Interestingly, mixed fractures were observed only in ARI 1 specimens; all ARI 0, ARI 2 and ARI 3 specimens showed adhesive fractures (Table 4b).

22 % of all specimens showed after debonding no adhesive on the enamel surface (ARI 0, Table 3), i.e. fractures in the adhesive-enamel interface only. In 63 % of all specimens the adhesive detached from more than half of the enamel surface (ARI 1, Table 3) showing in only 29 % of these cases – subjectivelly rather small – cohesive fracture areas within a mixed fracture mode (Table 4b); in other words they presented in the largest part of their (cumulative) area fractures in the adhesive-enamel interface. These findings show that the fractures took place mainly at the adhesive-enamel interface for the majority of all specimens. Thus, the SBS values of this experiment characterize essentially the strength of the adhesive-enamel interface.

Limitations

We used bovine incisors in our study; therefore, the results may not be fully transferable to humans. It should also be considered, that human lingual surfaces show different enamel micropatterns than labial ones [8]. The experiments showed high standard deviations of approximately 25 % in the acid etching groups and even 38% in the sandblasting-only group. However, almost all SBS studies, including the ones involving human teeth, demonstrated similarly high standard deviations. This behaviour can be attributed to the random character of many factors influencing crack initiation and propagation, for example, the existence of areas of stress concentration or flaws in the materials. In vitro SBS experiments do not necessarily give clear conclusions for the clinical behaviour of specimens, most importantly for long-term failure rate. The study was based on direct bonding, i.e. studying the enamel-adhesive-bracket interface. However, indirect bonding is common in the lingual technique, which means that the enamel-adhesive-adhesive-bracket interface should be investigated in a future study.

Conclusions

In laboratory conditions, bovine enamel sandblasting before acid etching, regardless of the used air pressure and powder granulation, did not influence shear bond strength compared to acid etching alone. Sandblasting-only reduced the shear bond strength by approximately 67 % compared to acid etching and produced less residual resin on the tooth after debonding; therefore, it cannot substitute acid etching. The clinical use of adjunct enamel sandblasting prior to etching for enhancing bond strength as often proposed for the lingual technique has to be questioned.

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Compliance with Ethical Standards

Conflict of Interest

The authors declare that they have no conflict of interest.

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Ethical approval

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

Informed consent

For this type of study, formal consent is not required.

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Fig 1 Sandblasting devices

The Microetcher CD (above) (Danville Materials, San Ramon, California, USA) was attached to the turbine hose of the dental unit and the air pressure was controlled through the pedal between 1.2 and 3.5 (±0.2) bar. The pedal was adjusted to the lowest setting of 1.2 (±0.2) bar to achieve the maximum contrast to the other group. The Microetcher IIA (below) (Danville Materials, San Ramon, California, USA) was attached directly to the compressor hose before the dental unit with an air pressure of 5.7 bar.

Fig 2a Specimen after bracket bonding

Fig 2b Shear bond strength testing according to DIN 13990:2017-04

A specimen consisting of a bonded bracket on a bovine tooth embedded in a cylindrical resin base (Technovit 4004, Heraeus-Kulzer®, Hanau, Germany), fixed in the ZMART.PRO® testing machine (Zwick GmbH & Co. KG, Ulm, Germany) and loaded through a stainless steel blade, which was manually held during the experiment.

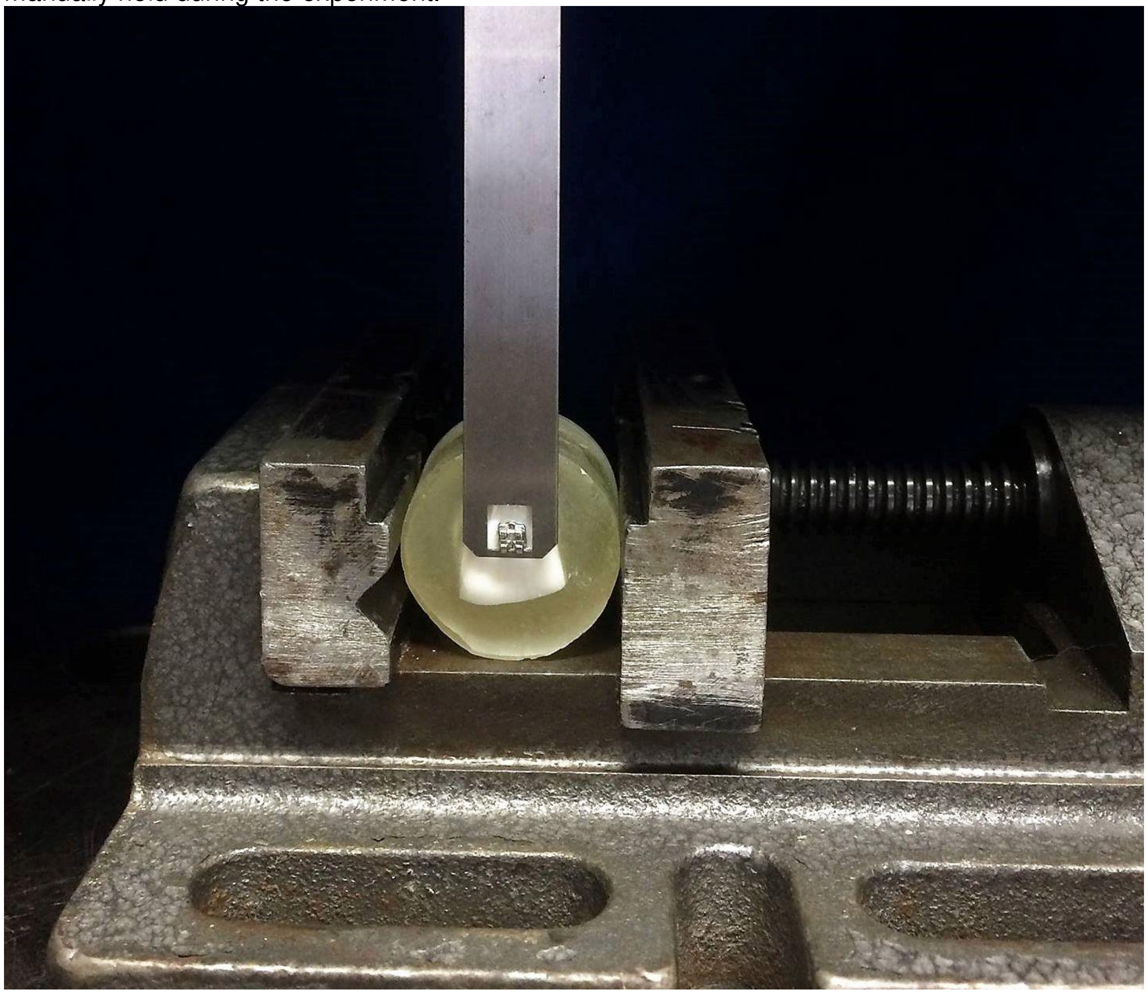
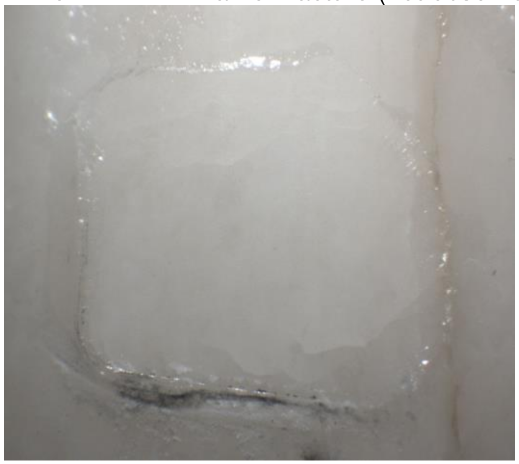
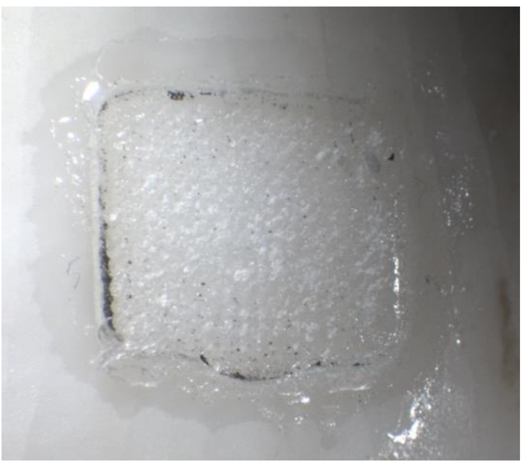


Fig. 3 Examples of enamel surfaces after shear strength testing illustrating different ARI values

a. ARI 0: 0 % adhesive on the enamel surface
b. ARI 1: <50 % adhesive on the enamel surface
c. ARI 2: >50 % adhesive on the enamel surface
d. ARI 3: 100 % adhesive on the enamel surface
e. ARI 4: Enamel fracture (not observed in this study)





5,00 mm

Fig. 4 Results of the shear bond strength testing

s: sandblasting only with 27 µm Al_2O_3 at 1.2 (±0.2) bar with MicroEtcher CD

a: acid etching only

s1a: sandblasting with 27 µm Al_2O_3 at 1.2 (±0.2) bar with MicroEtcher CD with subsequent acid etching

s2a: sandblasting with 50 µm Al_2O_3 at 5.7 bar with MicroEtcher IIA with subsequent acid etching

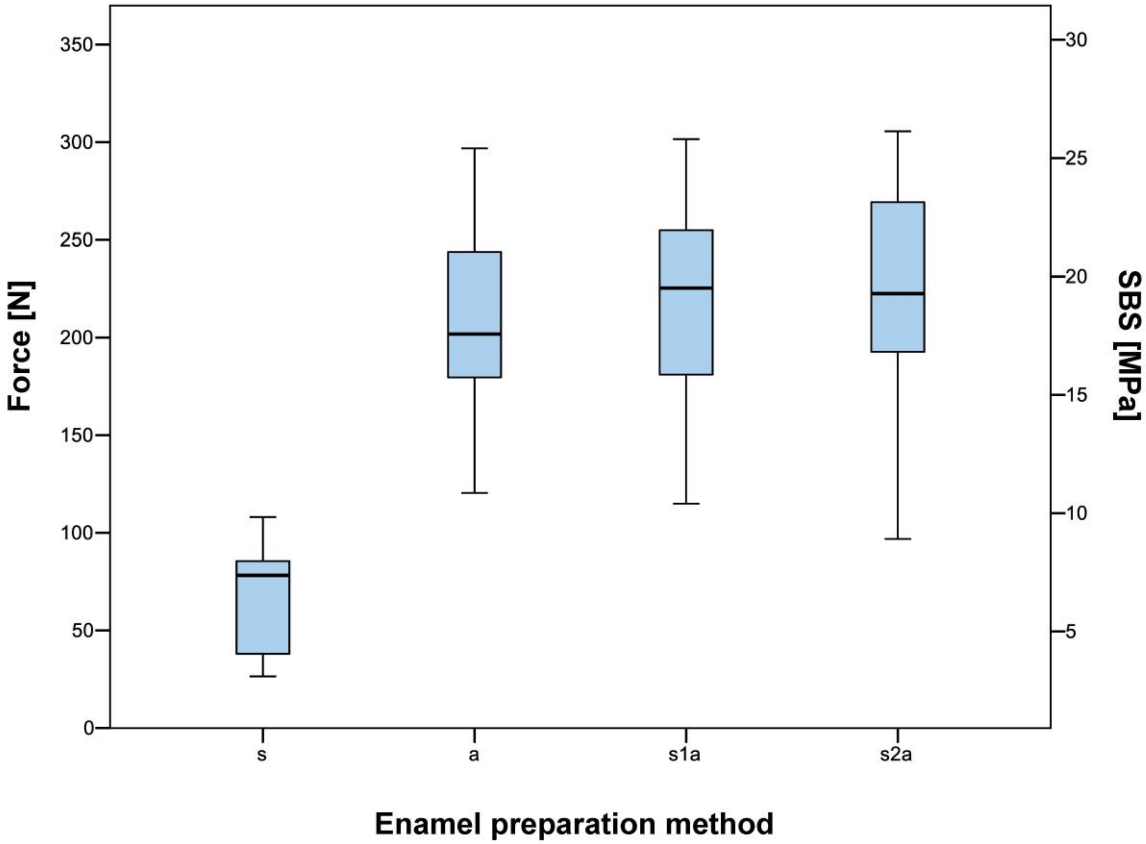


Fig. 5 ARI values

Fisher's Exact test showed a significant influence of the enamel preparation protocol on the ARI ($p<0.001$). Post hoc explorative comparison with an additional Fisher's exact test between a, s1a and s2a indicated no significant difference between the acid etching only and the two sandblasting and etching groups ($p=0.13$). No significant difference was found between the two sandblasting and etching groups (s1a & s2a) ($p=0.60$) when tested with a separate Fisher's exact test.