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ORIGINAL ARTICLE

Effects of reducing light-curing time of a high-power LED device on shear bond strength of brackets

Layene Figueiredo Almeida[1] · **Lidia Parsekian Martins**[1] · **Renato Parsekian Martins**[2,3]

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Abstract

Purpose To assess the effects of reducing the curing time of a high-power light-emitting diode (LED) unit (Valo, Ultradent, South Jordan, UT, USA) on shear bond strength (SBS) of metal brackets and on the amount of adhesive remnant of two orthodontic composites.

Methods Eighty human premolars were divided into four groups (G1–4) according to curing time and composite: G1 (Transbond XT, 6 s), G2 (Opal Bond MV, 6 s), G3 (Transbond XT, 3 s), and G4 (Opal Bond MV, 3 s). Twenty-four hours after bonding, brackets were subject to a SBS test performed with a universal testing machine. Enamel surface was analyzed by SEM and the amount of adhesive remnant was assessed by the Image J software area calculation tool. Two-way analysis of variance was used for statistical analysis of SBS data, while Friedman and Mann–Whitney post hoc tests were used to analyze data on the amount of adhesive remnant.

Results Time and composite significantly affected SBS ($p < 0.001$). The 6 s curing showed a higher SBS value (21.56 MPa) in comparison to 3 s curing (15.79 MPa). Transbond XT composite showed a significantly higher SBS value (21.06 MPa) compared to Opal Bond MV (16.29 MPa). After the SBS test, Opal Bond MV showed a significantly greater amount of composite adhered to enamel ($p < 0.001$).

Conclusion Reducing exposure time from 6 to 3 s significantly decreased mean values of SBS, even with the use of a high-power LED unit. Reduction in time did not affect the amount of adhesive remnant.

Keywords Light curing of dental adhesives · Orthodontic brackets · Dental bonding · Dental enamel · Dental cements

Layene Figueiredo Almeida, DDS, MS
layenea@gmail.com

Prof. Lidia Parsekian Martins, DDS, MS, PhD
lmartins@foar.unesp.br

✉ Prof. Dr. Renato Parsekian Martins, DDS, MS, PhD
dr_renatopmartins@hotmail.com

[1] Program of Orthodontics, Universidade Estadual Paulista, Araraquara, Brazil

[2] Department of Orthodontics, Universidade Estadual Paulista, Araraquara, Brazil

[3] Private practice, Rua Carlos Gomes, 2158, 14801340 Araraquara, SP, Brazil

Auswirkungen der Verkürzung der Lichthärtezeit einer Hochleistungs-LED-Lampe auf die Scherbindungsfestigkeit von Brackets

Zusammenfassung

Ziel Untersucht wurden die Auswirkungen der Verkürzung der Polymerisationszeit einer Hochleistungs-LED-Lampe („light-emitting diode"; Valo, Ultradent, South Jordan/UT, USA) auf die Scherbindungsfestigkeit (SBS) von Metallbrackets und auf die Menge der verbliebenen Adhäsivreste von 2 kieferorthopädischen Kompositen.

Methoden Achtzig menschliche Prämolaren wurden in 4 Gruppen (G1-4) nach Aushärtezeit und Zusammensetzung eingeteilt: G1 (Transbond XT, 6s), G2 (Opal Bond MV, 6s), G3 (Transbond XT, 3 s) und G4 (Opal Bond MV, 3s). 24 h nach Bonding wurden die Brackets einem SBS-Test mittels Universalprüfmaschine unterzogen. Die Schmelzoberfläche wurde rasterelektronenmikroskopisch untersucht und die Menge der Kunststoffreste mittels des Flächenberechnungstools Image J ermittelt. Für die statistische Analyse der SBS-Daten diente die 2-way ANOVA, die Adhäsivreste wurden mit den Post-hoc-Tests von Friedman und Mann-Whitney ausgewertet.

Ergebnisse Sowohl Polymerisationszeit als auch Komposit nahmen signifikanten Einfluss auf die Scherbindungsfestigkeit ($p < 0{,}001$). Die Polymerisationszeit von 6s ergab einen durchschnittlich höheren SBS-Wert (21,6 MPa) im Vergleich zur kürzeren Aushärtung von 3s (15,8 MPa). Der durchschnittliche SBS-Wert von Transbond XT lag mit 21,1 MPa signifikant höher als der von Opal Bond MV (16,3 MPa). Opal Bond MV hinterließ nach dem SBS-Test eine größere Menge Komposit auf dem Schmelz ($p < 0{,}001$).

Fazit Nach verkürzter Polymerisationszeit von 3 s fielen die durchschnittlichen SBS-Werte signifikant niedriger aus. Die verkürzte Polymerisationszeit nahm keinen Einfluss auf die Menge der verbliebenen Adhäsivreste.

Schlüsselwörter Lichthärtung von dentalen Adhäsiven · Kieferorthopädische Brackets · Bonding · Zahnschmelz · Zahnzemente

Introduction

Bracket bonding is one of the most time-consuming procedures in orthodontics. For this reason, reducing the time required for light curing of composites would increase treatment efficiency and provide patients with greater comfort. Light-emitting diode(LED)-based units are the most commonly used curing devices and have been reported to achieve satisfactory results with significantly reduced light-curing times of 10 [9, 18, 27] and 8 s [31]. However, studies that have reported a decrease in curing times were conducted with LED devices with a light intensity of 1000 mW/cm^2, which might suggest that devices with an intensity of about 3200 mW/cm^2 [17] could further reduce the light-curing times.

It was recently shown that a 1520 mW LED (producing a light intensity of 3200 mW/cm^2, according to the manufacturer) can achieve close to 90% composite conversion in 3 s, depending on the type of composite cured [1] (60% conversion is considered adequate). A clinical trial has also shown that brackets could be bonded using a 6 s cure with such a device [30]. However, the shear bond strength (SBS) of brackets subject to an even larger reduction of light-curing time, such as 3 s, by high-power LED has not been tested. Moreover, the types of adhesive failures during bracket debonding have not been evaluated.

Thus, the aim of the present study is to assess the effects of reducing the curing time using a high-power LED device on the adhesion strength of metal brackets in vitro and on the adhesive remnant of two orthodontic composites.

Materials and methods

The sample size calculation was carried out using average (M) and standard deviation (SD) data from the literature (M = 9.5, SD = 43 [19], M = 4.99, SD = 1.00 [8]). Setting a significance level of 5% and power at 80%, sample sizes of 10 and 18 teeth were calculated; however, a larger sample with two additional teeth (10%) was chosen due to the possible occurrence of fractures.

A total of 80 human premolars that had not previously had bonded brackets and with buccal surfaces that were free of caries, fracture, and restoration were collected from the universities' tooth bank and randomly divided into four groups to be subjected to the various bonding protocols. This investigation was approved by the ethics and research committee of the Faculdade de Odontologia de Araraquara—UNESP (CAAE: 32126914.5.0000.5416). The teeth were stored in distilled water at 4 °C for no longer than 3 months according to ISO standard 11405:2015.

In group 1, brackets were bonded with Transbond XT (3M/Unitek™, Monrovia, CA, USA) along with its adhesive, while in group 2, Opal Bond MV composite and Opal Seal adhesive (OPAL Orthodontics, Ultradent, South Jordan, UT, USA) were used. A 6 s (3 s mesially and 3 s

Table 1 Description of the groups tested
Tab. 1 Beschreibung der untersuchten Gruppen

Group	Adhesive system	Light-curing time (s)	*n*
1	Transbond XT composite + adhesive	6	20
2	Opal Bond + Opal Seal	6	20
3	Transbond XT composite + adhesive	3	20
4	Opal Bond + Opal Seal	3	20

Table 2 Two-way ANOVA outcomes, in which the influence of light-curing time and the type of composite were assessed for shear bond strength
Tab. 2 Two-way ANOVA zur Untersuchung des Einflusses der Polymerisationszeit und der Art des Komposits auf die Scherbindungsfestigkeit

Factor	Mean square	F	*p*-value
Time	453.96	17.42	<0.001
Composite	667.19	25.60	<0.001
Time*Composite	4.88	0.19	0.67

Table 3 Mean, standard deviation (SD), and confidence interval (95%) values for the variables time and composite (in MPa)
Tab. 3 Mittelwert, Standardabweichung (SD) und Konfidenzintervall (95%) für die Variablen Zeit und Komposit (in MPa)

Variables		Mean	SD	Confidence interval	
				Lower limit	Upper limit
Time	3	15.79	5.52	14.18	17.40
	6	21.57	5.65	19.96	23.17
Composite	Transbond XT	21.06	6.31	19.45	22.67
	Opal Bond	16.30	5.31	14.69	17.90

Table 4 Outcomes of shear bond strength (SBS) averages of the groups tested, along with the standard deviation (SD), and minimum (min) and maximum (max) values (MPa)
Tab. 4 Ergebnisse der SBS-Mittelwerte der untersuchten Gruppen, Standardabweichung (SD) sowie minimale (min) und maximale (max) Werte (MPa)

Group	Time	Composite	Mean	SD	Min	Max
1	6	TB	23.70	6.51	11.20	37.56
2	6	OB	19.43	3.70	12.21	28.37
3	3	TB	18.42	4.96	6.58	26.33
4	3	OB	13.16	4.85	6.88	21.71

TB Transbond XT, *OB* Opal Bond

distally) light-curing procedure was used for both groups. In groups 3 and 4, the same composites and adhesives were used, but they were light cured for 3 s on one surface only (Table 1). All adhesives were light cured for 3 s before the composites were cured either 6 or 3 s, according to the respective group. The light-curing device was the VALO Cordless third-generation LED (Ultradent, South Jordan, UT, USA), using the Xtra curing mode (intensity was 3200 mW/cm^2 according to the manufacturer). Using a Fieldmaster energy meter (Coherent, Santa Clara, CA, USA), a power of 1757 mW was found, thus, resulting in an intensity of 2246 mW/cm^2, based on a 9.6 mm diameter tip. The LED unit was also evaluated for variation in power, which was not used in the present report.

The teeth were secured into 2 cm-high and 20 mm-round polyvinyl chloride (PVC) tubes, with self-curing acrylic resin (Resina acrílica JET, Produtos Odontológicos Clássico, São Paulo, BR). The center of the buccal surface was positioned perpendicular to the tube base with the aid of a metal set square and the specimens were stored in distilled water at 4 °C until bracket bonding, according to ISO/TS 11405/2014.

Prior to bonding, enamel surfaces were cleaned with oil-free pumice paste and rubber cup for 15 s, followed by rinsing with tap water and drying with water-free compressed air for 10 s.

New Avex (Opal Orthodontics, South Jordan, UT, USA), Roth prescription, 0.018 in metal brackets with a 11.045 mm^2 base (measured by a Coolant Proof Micrometer IP65 caliper, Mitutoyo, Aurora, IL, USA) were bonded to the premolars, following the respective bonding protocol for each group.

After bonding, specimens were immersed in distilled water and stored at 37 °C for 24 h until SBS tests were carried out. A custom-made chisel was attached to an EMIC DL 2000 (INSTRON, ITW, São José dos Pinhais, BR) universal testing machine with 2500 N load cell and subjected to a vertical movement at a speed of 0.5 mm/min. Maximal SBS was registered in newton (N) by the dedicated test script (TESC) software and calculated into megapascal (MPa) for statistical analysis.

After the test, the buccal surfaces were molded with light-body polyvinylsiloxane (Elite HD, Zhermack®, Badia Polesine, IT), and impression copings were made with epoxy composite (Epofix, Struers, Ballerup, DK). In order to quantify adhesive remnant, copings were coated with a gold layer under a 50 s cycle and photographed by scanning electron microscopy (JSM, 6380LV, JEOL, Tokyo, JP) under 20× magnification and 12 kV (Fig. 1). One operator determined the percentage of remaining composite adhered to teeth comparing it to the bracket base area, with the aid of the Image J software, v. 1.36 (National Institutes of Health, Rockville, MD, USA). Measurements were repeated after one week in order to conduct error analysis by the Bland–Altman plot [5, 13], and the mean value of both measures was used for statistical analysis.

Statistical analysis of the data was carried out by two-way analysis of variance (ANOVA) with the significance level set at 95% ($p < 0.05$). Data on the percentage of ad-

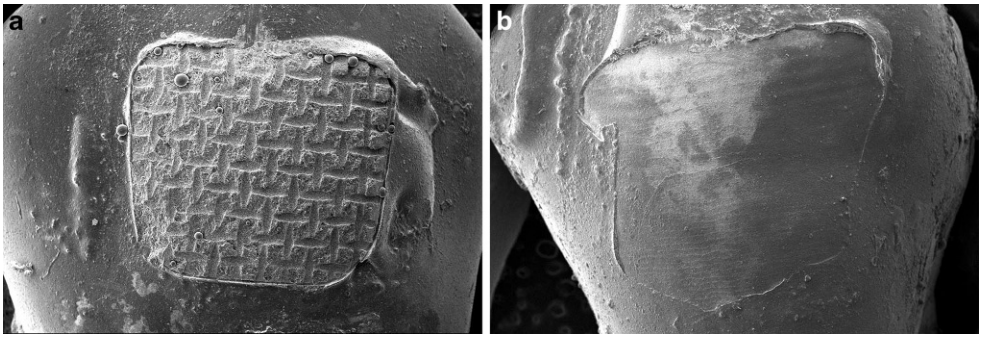

Fig. 1 **a** Scanning electron microscope (SEM) photograph under 20× magnification showing a specimen with almost 100% adhesive on the enamel surface. **b** SEM photograph with no adhesive on the enamel surface
Abb. 1 **a** Rasterelektronenmikroskopische Aufnahme, Vergr. 20:1, Probe mit nahezu 100% Adhäsiv auf der Schmelzoberfläche. **b** Rasterelektronenmikroskopische Aufnahme, kein Adhäsiv auf der Schmelzoberfläche

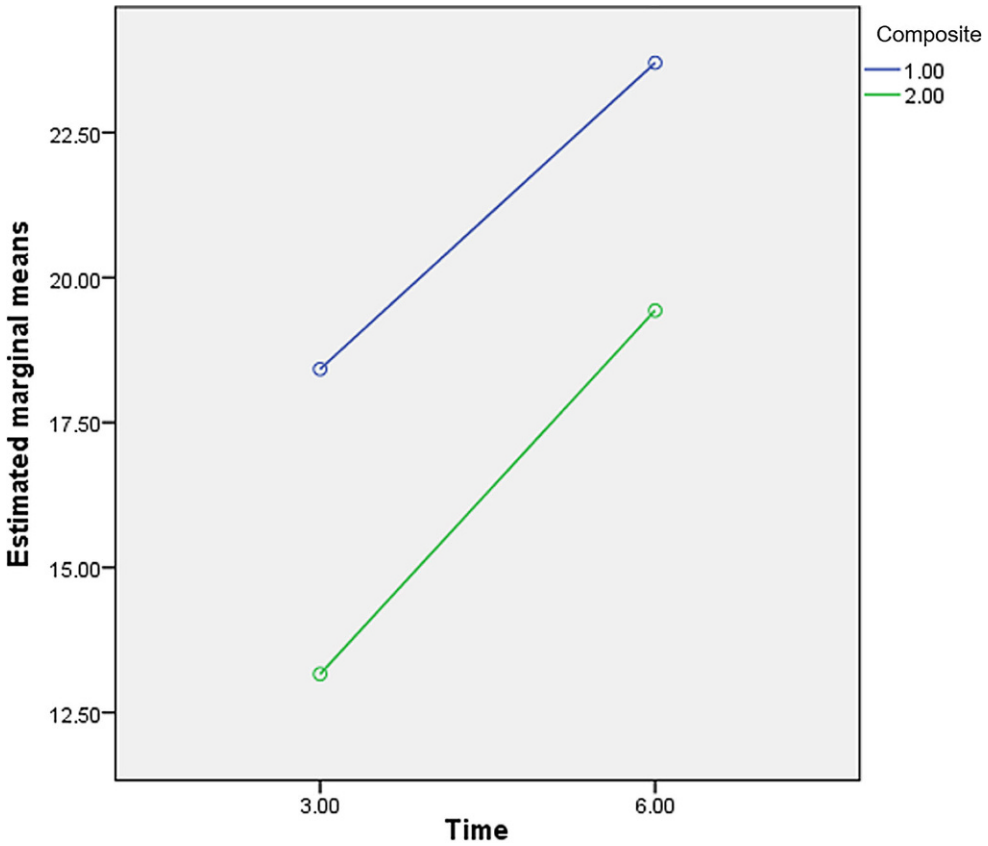

Fig. 2 Adhesion strength in relation to the variables resin and time (s), showing no interaction
Abb. 2 Scherbindungsfestigkeit in Relation zu den Variablen „resin" und „Zeit" (s). Es liegen keine Wechselwirkungen vor

hesive remnant were assessed by Friedman and post hoc Mann–Whitney statistical tests with the significance level set at 95% ($p < 0.05$).

Results

Time significantly affected SBS values between groups ($p < 0.001$; Table 2). The 3 s interval produced an average SBS of 15.79 MPa, whereas the 6 s interval produced an average of 21.57 MPa (Table 3).

The type of composite significantly affected SBS values ($p < 0.001$; Table 2). Transbond XT composite produced a SBS of 21.06 MPa, whereas Opal Bond produced an average of 16.30 MPa (Table 3). There was no interaction between the curing time and type of composite ($p = 0.667$, Tables 2 and 4; Fig. 2).

Reproducibility of the process for measuring the amount of adhesive remnant was assessed by Bland–Altman plot (Fig. 3), estimated with 95% limits of agreement. Bias was 0.038, and the calculated limits of agreement suggest

Table 5 Mann–Whitney test was used to assess the influence of composite and time on the amount of remaining material on enamel surface ($p = 0.025$[a])

Tab. 5 Mann-Whitney-Test ermittelt den Einfluss von Komposit und Zeit auf die Menge des verbliebenen Adhäsivs auf der Schmelzoberfläche ($p = 0{,}025$[a])

Variable		Percentage			Mann–Whitney ($p < 0.025$)
		25	50 (Median)	75	
Composite	TB	8.0	11.0	19.0	<0.001
	OB	19.0	38.0	74.0	
Time (s)	3	9.0	18.0	44.0	$p = 0.509$
	6	13.2	21.5	39.2	

[a]Corrected by Bonferroni
TB Transbond XT, *OB* Opal Bond

Table 6 Distribution of fractures among groups

Tab. 6 Verteilung von Frakturen auf die Gruppen

Group	Number of fractures	Minimal stress (MPa)	Maximal stress (MPa)
1	5	21.68	27.04
2	1	21.36	21.36
3	2	19.96	26.33
4	0	–	–

Table 7 Adhesive remnant index (ARI) data distribution for the four study groups

Tab. 7 ARI(Adhesive Remnant/Residual Index)-Datenverteilung für die 4 untersuchten Gruppen

		ARI 0		ARI 1		ARI 2		ARI 3	
Group	*N*	*N*	%	*N*	%	*N*	%	*N*	%
1	15	0	0	15	100	0	0	0	0
2	19	1	5	12	63	6	32	0	0
3	18	1	5.5	16	89	1	5.5	0	0
4	20	0	0	13	65	7	35	0	0

that most measurements presented with differences between 0.24 and –0.16 mm².

Friedman test outcomes revealed significant differences between the four groups ($p = 0.006$) regarding the amount of adhesive remnant. The type of composite was significantly associated with the amount of adhesive remnant on the enamel surface ($p < 0.001$; Table 5). Opal Bond left more composite adhered to the tooth in comparison to Transbond XT (Table 5). There was no significant difference for the curing time ($p = 0.509$).

A total of eight specimens underwent fracture during the SBS test. The SBS registered in those specimens ranged from 19.96 to 27.4 MPa and fracture was more frequent in G1 (Transbond XT, 6 s; Table 6).

Discussion

Reducing exposure time from 6 to 3 s decreased bonding strength, even with the use of a high-power LED. This was an expected finding, since the degree of conversion for composites is directly proportional to the power absorbed by its photoactivators [6, 25]. Reduction in time from 40 to 10 s [27], from 20 to 10 s [9, 18, 27, 29] and even to 8 s [31] have already been shown to produce clinically acceptable outcomes; however, curing was performed with lower power LED devices, producing light intensities of 1000 mW/cm². More recently in a split-mouth clinical trial, the effects of curing brackets with a high power LED for 6 s [30] were evaluated and no difference was found compared to brackets cured with conventional light. Importantly, we have shown in vitro that a further decrease could be possible, which needs confirmation before starting further clinical trials examining even lower curing times.

It is very important to mention that the "clinically acceptable" SBSs values very often reported in the literature (from 5.9–7.8 MPa) have been empirically based on one personal opinion from an article published in 1975 [22], a time when bonding materials and procedures differed from those used today, such as etching time and chemicals used, as well as the adhesive systems, with acrylic resin being one of the main bonding materials [22]. Due to a lack of better references on the ideal strength, it is difficult to determine the optimal adhesion parameter. An alternative value for those cited in the literature as ideal could be estimated from maximal biting force. If the adult maximal biting force (285.01 N for men and 253.99 N for women) [28] is divided by the bracket base area used in the present study (11.045 mm²), the result, of 25.8 and 22.99 MPa for men and women, respectively, would equal the maximal pressure value a single bracket would be subjected to if exposed to mastication. The SBS values found in this paper for 6 and 3 s were 21.57 and 15.79 MPa, respectively, and are below that estimated value, but significantly above the values of 5.9–7.8 MPa [22].

Nevertheless, while high bonding strengths are needed in order to keep orthodontic brackets in place during treatment, extremely high values might increase the risk for enamel fracture at the time of debonding. In our sample, eight fractures occurred in specimens subjected to the shear bond strength test. Five of them occurred after Transbond XT was cured for 6 s, with SBS values ranging from 21.7 to 27.0 MPa; two occurred after Transbond XT was light cured for 3 s, with values ranging from 20.0 to 26.3 MPa; and one occurred after Opal Bond MV was cured for 6 s with a SBS value of 21.36 MPa. Although the literature considers SBS values above 13 MPa as an increased risk for enamel fracture [3, 7, 21], we only found fractures with SBS values above 20 MPa. High values carry a risk for

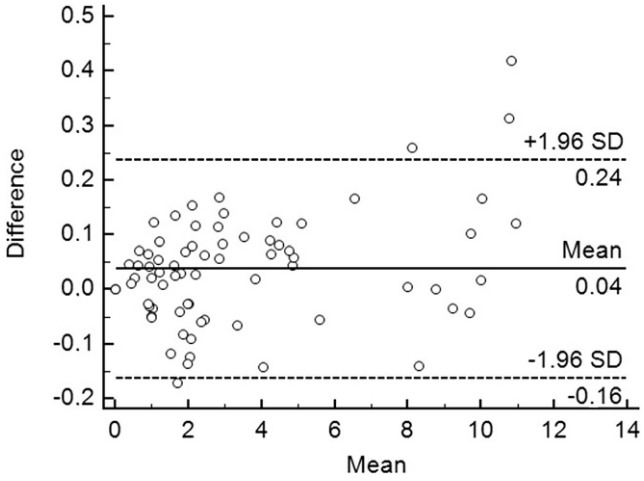

Fig. 3 Bland–Altman plot: association of the differences between the measured values and the mean values to assess reproducibility. *SD* standard deviation

Abb. 3 Bland-Altman-Plot: Assoziation zwischen der Messwertdifferenzen und dem Mittelwert zur Beurteilung der Reproduzierbarkeit. *SD* Standardabweichung

fracture at the time of debonding, but this finding should be considered with caution, since pure SBS is hardly ever applied to brackets to remove them clinically [4].

The type of composite affected SBS. Transbond XT showed a higher average SBS than Opal Bond MV at 6 s of curing and as curing time decreased this difference increased (Fig. 2 and Table 4). In general, composites tend to respond differently to curing since various factors affect that process, such as chemical composition and the type of light-curing unit [15, 24]. To date, no comparison between these two composites has been published using a high power LED with such a short curing time, even though their conversion degree has already been shown to be adequate after a curing time of 3 s [1]. Compared to what is considered adequate for immediate loading, i.e., 55% conversion degree [14], both composites showed an adequate degree of conversion: Transbond XT had a conversion degree above 60% while Opal Bond MV had a conversion degree above 80%.

The ISO/TS 11405:2015, as well as DIN 13990-1/-2 norms, suggest thermocycling with 500 cycles as one of the ways of storing teeth before mechanical testing, and it could have been a possible option in this study. However, while some studies have reported a significant decrease in strength values after thermocycling [9, 26], others have shown that thermocycling did not affect bond strength [11, 16, 23, 32]. These different results can be explained by the fact that conversion degree affects resin integrity when it is submitted to water storage and thermocycling. The reason for this effect is that inadequate light curing makes resin more permeable to water [12]. The adhesives used in this study showed a conversion degree above 60% even with a curing time of 3 s [1], which leads us to believe that thermocycling would not have changed our results.

The decrease of curing time did not have any significant influence on the amount of residual composite after the SBS test, but differences were found between the two commercial brands. After the application of Opal Bond MV, a greater amount of adhesive remained on the enamel surface, revealing a safer pattern of failure (Tables 5 and 6) in comparison to Transbond XT. Adhesive failure between bracket and composite seems to be the safest pattern of failure because enamel fracture is avoided due to less stress being transmitted to enamel at the time of debonding [20]. In the present study, the amount of residual composite was estimated by determining its area and comparing it to the bracket base area. This method appears to be more accurate and reproducible than visual inspection and the adhesive remnant index (ARI) due to it being quantitative rather than qualitative [2]. Since this method has not yet been reported in the literature, we have adjusted the percentages into ARI score (Table 7) in order to promote discussion of the subject.

The majority of the specimens showed an ARI score of 1, which means that less than 50% of composite remained on the enamel and is in agreement with previous reports where curing time was reduced with Transbond XT [18]. In contrast, similar studies [10, 31] found an ARI score of 3 (100% of adhesive on enamel surface with bracket base printing), which did not occur in any of our groups tested. This is probably due to the fact that none of them used irradiances similar to the one used in this study.

In bracket bonding, it is imperative for adhesion to be strong enough to allow the bracket to remain in place until completion treatment, and at the same time allowing safe debonding. We believe that SBS values ranging from 5.9 to 7.8 MPa are not high enough to bear masticatory forces and that a 6 s cure might produce an extremely high adhesion strength (21.57 MPa), increasing the risk of enamel fracture. Reducing curing time to 3 s produced a similar SBS average (15.79 MPa) to previous studies working with a 10 s cure time (SBSs of 13.5 MPa [27], 14.48 MPa [9], and 15.9 MPa [18]) which might be safer values when it comes to avoiding enamel fracture. When cured for 3 s, Opal Bond MV composite showed SBS values that were high enough but were not associated with enamel fracture, thus, seeming to have the best relationship when compared to the other groups. Nonetheless, we need to be careful when extrapolating these data directly to clinical practice because in vitro results might not directly reproduce the situation in the oral cavity. Therefore, we suggest that clinical studies be undertaken to confirm these in vitro results.

Conclusions

- The shear bond strengths obtained at 6 s intervals were significantly greater than at 3 s intervals when using a high-power LED device.
- Transbond XT composite presented higher shear bond strength values in comparison to Opal Bond MV composite.
- Reduction in time did not affect the amount of adhesive remnant.
- After the SBS test, Opal Bond MV composite showed a significantly greater amount of composite adhered to the enamel surface.

Compliance with ethical guidelines

Conflict of interest L.F. Almeida, R. Parsekian Martins and L. Parsekian Martins declare that they have no competing interests.

Ethical standards All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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