ORIGINAL ARTICLE
DOI: 10.5152/EssentDent.2026.25045

The Effect of Different Light Intensities of LED Curing Units on the Bond Strength of Next-Generation Self-Adhesive Coated Metal Brackets

Muhammed Veli Alparslan[1], Zeynep Çoban-Büyükbayraktar[2]

[1]Hospitadent Oral and Dental Health Hospital, Kayseri, Türkiye
[2]Department of Orthodontics, Sivas Cumhuriyet University Faculty of Dentistry, Sivas Türkiye

Cite this article as: Alparslan MV, Çoban-Büyükbayraktar Z. The effect of different light intensities of LED curing units on the bond strength of next-generation self-adhesive coated metal brackets. *Essent Dent.* 2026, 5, 0045, doi: 10.5152/EssentDent.2026.25045.

Abstract

Background: Effective orthodontic bonding relies on proper light-curing techniques, as variations in curing mode and intensity can influence adhesive performance and clinical outcomes. This study aimed to investigate the effects of light emitting diode (LED) curing unit intensity and exposure duration on the shear bond strength (SBS) of APC Flash-Free metal brackets under in vitro conditions.

Methods: Sixty human premolars were divided into three groups (n=20). All procedures were identical, except for light-curing parameters. The curing process was carried out using an LED light-curing unit (VALO Ortho; Ultradent Products, South Jordan, Utah). Group 1 was cured in standard power mode (1200 mW/cm²) for 1 × 10 seconds; Group 2 was cured in high power mode (3200 mW/cm²) for 2 × 3 seconds; and Group 3 was cured in quadrant high power mode (3200 mW/cm²) for 2 × 3 seconds. SBS tests were performed using an Instron machine (Lloyd LF Plus; Ametek, UK). Shear bond strength (SBS) values and Adhesive Remnant Index (ARI) scores were analyzed using the Kruskal-Wallis H test (α=0.05).

Results: The highest mean SBS was observed in the standard mode group, and the lowest in the quadrant high-power mode group, but differences were not statistically significant (P=.670). Curing modes also showed no significant effect on ARI scores (P=.293).

Conclusion: All tested modes showed comparable outcomes under in vitro conditions. For clinical applications, the use of the high-power mode is recommended, as it enables shorter polymerization durations; however, clinical studies or in vivo validation are required to confirm these findings.

Keywords: ARI score, bond strength, LED dental curing lights, orthodontic brackets

What is already known on this topic?

- *Adequate bracket–enamel bond strength is essential for the success of fixed orthodontic treatment and is influenced by multiple factors, including curing light characteristics, adhesive composition, and bracket-related variables.*
- *Different types of curing lights have been used in orthodontics, and variations in light intensity and exposure duration can affect the polymerization and mechanical properties of orthodontic adhesives.*
- *APC Flash-Free brackets improve bonding efficiency by eliminating adhesive flash, but evidence of their interaction with modern light emitting diode (LED) curing modes is limited.*

What does this study add on this topic?

- *Different application modes of a multi-mode LED curing unit showed no significant differences in bond strength or ARI scores for APC Flash-Free metal brackets.*
- *Comparable bonding performance was achieved across all tested curing modes under in vitro conditions.*
- *Although high-power LED modes allow shorter curing times, their clinical reliability requires confirmation through in vivo or clinical studies.*

INTRODUCTION

Bond strength between brackets and enamel is crucial for the success of fixed orthodontic treatment. Bond failure not only compromises treatment outcomes but also leads to prolonged treatment duration, reduced patient comfort, and increased costs.[1]

The type of curing light used significantly affects the effectiveness of polymerization. Quartz Tungsten Halogen (QTH) lamps, light emitting diodes (LEDs),[2] laser devices, and Plasma Arc Curing (PAC) units are frequently used in dental applications.[3] Traditionally,

Corresponding author: Zeynep Çoban-Büyükbayraktar
E-mail: dtzeynepcoban@gmail.com

Content of this journal is licensed under a Creative Commons Attribution-NonCommercial 4.0 International License.

Received: March 24, 2025
Revision Requested: June 20, 2025
Last Revision Received: January 4, 2026
Accepted: February 10, 2026
Publication Date: August 21, 2026

blue light generated by halogen lamps has been widely employed in orthodontics. However, over time, the filter in these devices deteriorates, leading to reduced efficiency and longer curing times.[4] To overcome these limitations, LED curing units with low voltage and high-intensity light at specific wavelengths have been developed.[3]

Self-adhesive brackets that polymerize under light were first introduced in 1991 by 3M Unitek (Monrovia, CA, USA). Since then, various versions of APC brackets have been developed.[5] The latest generation, APC Flash-Free brackets, was introduced by 3M Unitek and is designed to eliminate excess adhesive flash.[6] Unlike other self-adhesive brackets, APC Flash-Free brackets, when pressed against the enamel surface, release a transparent, low-viscosity adhesive from the base, forming a meniscus-like adhesive band, eliminating the need for additional cleanup.[7]

Bond strength is influenced by several factors, including the type of curing light, duration of curing, type and application time of acid, bracket base design and material, and the chemical composition of the adhesive.[1,8] However, among these factors, the curing light intensity and exposure duration play a particularly critical role in determining the polymerization efficiency of the adhesive. As the light intensity increases, a higher degree of polymerization is achieved, resulting in improved mechanical properties and bond strength.[9,10] Conversely, shortening the curing time may reduce the degree of conversion and weaken the physical properties of the adhesive.[11] Although orthodontic adhesives are required to have high bond strength, they must also possess sufficiently low debonding strength to allow for safe bracket removal at the end of treatment without causing enamel damage.[12]

Numerous studies have examined how curing light intensity and exposure time affect the bond strength and fracture resistance of orthodontic adhesives.[13-15] Considering the clinical need for orthodontists to improve time efficiency during the placement of fixed appliances, it remains essential to determine the minimum curing duration and corresponding light intensity that ensure clinically acceptable bond strength. However, limited evidence exists on how modern LED units with multiple intensity modes interact with the adhesive properties of APC Flash-Free metal brackets, and on the minimum effective curing parameters required to achieve optimal bonding with these systems. The present study aims to fill this gap by investigating how light intensity and curing time influence the bond strength of APC Flash-Free brackets bonded to premolar teeth extracted for orthodontic purposes.

MATERIAL AND METHODS

Ethical approval for this study was obtained from the Non-Interventional Clinical Research Ethics Committee of Sivas Cumhuriyet University (Decision No: 2022-02/30, dated February 16, 2022). The study was conducted in accordance with the principles outlined in the Declaration of Helsinki. Designed as an experimental study, it was carried out using 60 human premolar teeth. These teeth were collected from patients who applied to the Department of Orthodontics at the Faculty of Dentistry, Sivas Cumhuriyet Faculty of Dentistry, and underwent premolar extraction due to crowding. Informed consent was not needed because this study used only extracted premolar teeth.

For sample selection, only teeth with no caries or restorations, undamaged during extraction, and with smooth buccal surfaces were included. Teeth with any surface damage caused by chemical agents were excluded from the study. Based on a power analysis with an effect size (f) = 0.42, $\alpha = 0.05$, $\beta = 0.20$, and power $(1-\beta) = 0.80$, it was determined that each group should include 20 teeth, and the calculated test power was $P = .8169259$.[16] The selected effect size (f = 0.42) was determined with reference to the example calculations and recommendations provided by Suresh and Chandrashekara,[16] who demonstrated similar parameters for studies with comparable group designs. This medium-to-large effect size was considered to represent a clinically meaningful difference among groups.

Following extraction, the teeth were stored in glass containers at room temperature in a 0.1% thymol solution for approximately three months to prevent enamel degradation. The solution was replaced monthly to avoid bacterial growth.

In this study, APC Flash-Free Adhesive Coated Appliance Victory Series metal brackets (3M Unitek, Monrovia, CA, USA) were used for all groups. The teeth were randomly divided into three groups, with 20 teeth assigned to each group.

Group 1: The buccal surfaces of the teeth were etched with i-GEL 37% phosphoric acid etching gel (Lithuania) for 30 seconds and then rinsed with water for another 30 seconds. After drying, Transbond XT Light Cure Adhesive Primer (3M Unitek, Monrovia, CA, USA) was applied. Since the bracket base contained self-adhesive material, the bracket was taken directly from its individual package and placed onto the tooth surface. The adhesive was then cured using an LED light-curing device (VALO Ortho; Ultradent Products, South Jordan, Utah), held perpendicular and as close as possible to the bracket-tooth interface, and activated in standard power mode (1200 mW/cm^2) for 1 × 10 seconds (Figure 1). The procedure was carried out under standardized conditions by a single specialized orthodontist.

Group 2: The same procedures as in Group 1 were followed. Curing was performed using the LED light-curing device in high power mode (3200 mW/cm^2) for 2 × 3 seconds.

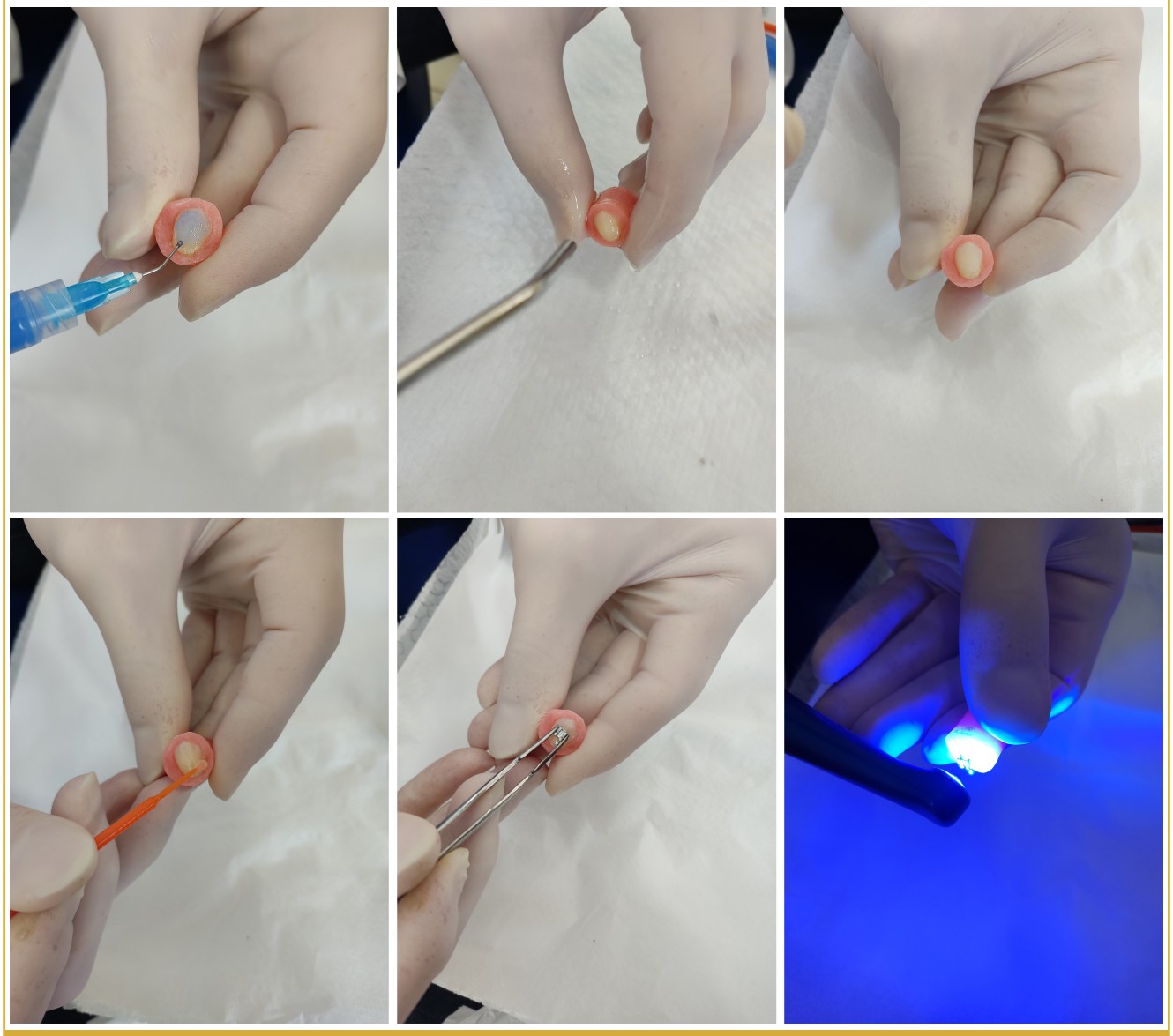

Figure 1. Stages of bracket application; (A) Acid etching. (B) Rinsing. (C) Drying. (D) Adhesive application on the tooth surface. (E) Bracket placement. (F) Light curing.

Group 3: All steps were identical to those in Group 1. The adhesive was cured using the LED light-curing unit in quadrant high power mode (3200 mW/cm^2) for 2 × 3 seconds.

To enhance the clinical relevance of in vitro studies, it is necessary to simulate in vivo conditions, particularly through thermal cycling. In the present study, all specimens were subjected to thermal cycling to replicate the thermal variations of the oral environment and to achieve a more accurate evaluation of bracket bond strength. To simulate intraoral temperature fluctuations, specimens were subjected to 10,000 thermal cycles between 5°C and 55°C, with 30-second immersions in each bath and a 5-second transfer interval.[17]

For the SBS test, the teeth were embedded in cold acrylic resin within custom-made molds, fixed just below the cervical margin. The bond strength test was conducted using an Instron Testing Machine (Lloyd LF Plus; Ametek Inc, Leicester, UK). This device has two parallel arms, one fixed and one movable, allowing force to be applied in a controlled direction to the specimen placed on the fixed arm (Figure 2). The applied force was recorded digitally in Newtons with 1N precision. In this study, compressive force was applied at a speed of 0.5 mm/min between the bracket and tooth surface until the bracket detached. The results were converted into megapascals (MPa = N/nm^2 × 0.980665) and recorded.

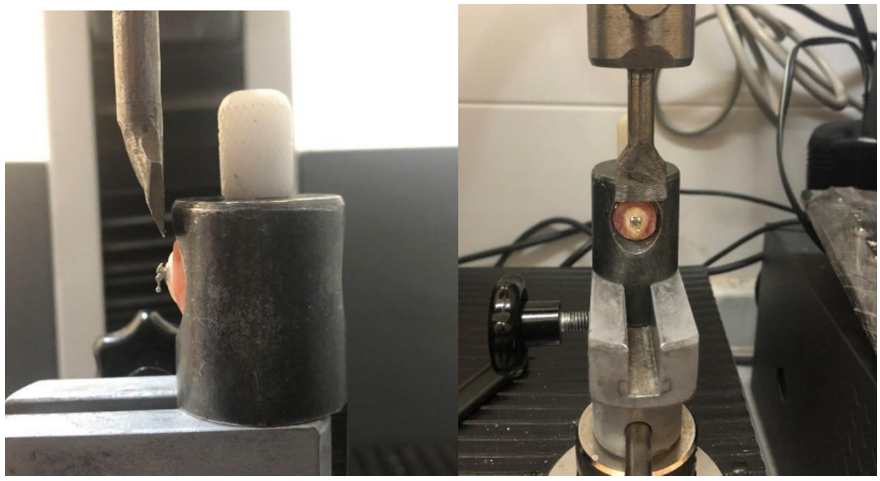

Figure 2. Side view and front view of the Instron testing device during the procedure.

Following the debonding procedure, the buccal surfaces of the teeth were examined by a single examiner using a Nikon SM2800 (Nikon Corporation, Tokyo, Japan). The remaining adhesive on the enamel surfaces was evaluated using the Adhesive Remnant Index (ARI), a standardized scoring system introduced by Årtun and Bergland in 1984 to quantify the amount of adhesive residue after bracket removal.[18] The ARI has been widely adopted in orthodontic research to assess the quality of bonding and debonding procedures. The scoring system ranges from 0 to 3, based on the amount of adhesive left on the enamel surface:

- Score 0 – No adhesive remains on the tooth surface.
- Score 1 – Less than 50% of the adhesive remains on the tooth surface.
- Score 2 – More than 50% of the adhesive remains on the tooth surface.
- Score 3 – The entire adhesive remains on the tooth surface, with no adhesive observed on the bracket base.

Statistical Analysis

The data obtained from the study were analyzed using SPSS version 23.0 (IBM Corp., Armonk, NY, USA). The assumptions of parametric tests were evaluated using the Shapiro-Wilk test. Continuous variables are summarized as mean and standard deviation, while categorical variables are presented as frequency and percentage. The chi-square test was used to analyze the relationships between categorical variables. Since the continuous variables did not meet the assumptions for parametric testing, comparisons between groups were performed using the Kruskal–Wallis *H* test. A significance level of 0.05 was adopted for all statistical analyses.

RESULTS

Sixty brackets were evaluated, with 20 brackets assigned to each of the three experimental groups. Shear bond strength (SBS) values and ARI scores were compared among the groups to assess differences in bonding performance.

Statistical analysis showed no significant difference in SBS among the groups ($P = .670$). Descriptive statistics and comparative data for bond strength are presented in Table 1.

The comparison of ARI scores also revealed no statistically significant difference between the groups ($P = .293$), as shown in Table 2.

When ARI scores were categorized and analyzed by group, the differences remained statistically insignificant ($P = .074$). The distribution of ARI scores is presented in Table 3.

DISCUSSION

Studies that investigate the bond strength of orthodontic brackets frequently use premolar teeth.[17,19] Although these

Table 1. Comparison of Shear Bond Strength Among Groups

	Shear Bond Strength (MPa)		
Groups	Mean ± Standard Deviation	Minimum–Maximum	*P*
Group 1 (n=20)	10.9 ± 2.6	6.2–15.5	.670*
Group 2 (n=20)	10.8 ± 2.7	5.8–14.4	
Group 3 (n=20)	10.2 ± 3.8	5.2–17.7	

* Kruskall–Wallis *H* test

Table 2. Comparison of ARI Scores Among Groups

	ARI Scores		
Groups	Mean ± Standard Deviation	Minimum–Maximum	*P*
Group 1 (n=20)	1.9 ± 1.2	0–3	.293*
Group 2 (n=20)	2.1 ± 0.9	0–3	
Group 3 (n=20)	1.6 ± 1.2	0–3	

* Kruskall–Wallis *H* test
ARI, Adhesive Remnant Index.

Table 3. Comparison of the Distribution of ARI Scores Among Groups

ARI Scores	Group 1 n (%)	Group 2 n (%)	Group 3 n (%)	*P*
0	3 (15)	1 (5)	4 (20)	.074*
1	6 (30)	4 (20)	7 (35)	
2	0 (0)	7 (35)	3 (15)	
3	11 (55)	8 (40)	6 (30)	

* Chi-square test.
ARI, Adhesive Remnant Index.

studies are conducted under in vitro conditions, researchers often prefer premolar teeth to obtain results that reflect clinical conditions more accurately. In the present study, premolar teeth without caries or restorations, with intact crowns after extraction, and with smooth buccal surfaces were selected to maintain standardization.

Some studies have indicated that self-adhesive brackets have lower bond strength compared to conventionally bonded brackets.[7,20] In this study, APC Flash-Free Adhesive Coated Appliance Victory Series metal brackets, manufactured by 3M Unitek (Monrovia, California), were used. The use of a self-adhesive system minimized operator-dependent variability during adhesive application and ensured procedural consistency.

Modern high-power LED units operating at 3200 mW/cm² may generate heat; however, previous studies indicate that the associated pulpal temperature increase remains well below the critical 5.5°C threshold when used for clinically acceptable exposure durations.[21,22] In our study, the exposure times were short and followed manufacturer recommendations, making clinically harmful thermal accumulation unlikely.

Previous studies have shown that 0.1% thymol does not adversely affect bond strength or microleakage at enamel or dentin margins.[23,24] It has also been reported that teeth stored in thymol for up to two months remain suitable for mechanical in vitro testing, whereas 12-month storage significantly reduces enamel and dentin microhardness.[25] In our study, the teeth were stored in thymol for approximately three months, which falls within the commonly accepted range in the literature.

Regarding enamel conditioning, similar to our study, many orthodontic in-vitro studies have used a 30-second phosphoric acid etching protocol.[26,27] More recent evidence, however, indicates that an etching time of approximately 15 seconds is sufficient for modern adhesive systems.[28] It has also been noted that etching can alter enamel roughness and microhardness within seconds, and etching longer than 30 seconds should therefore be avoided.[29]

Identifying a reliable method for assessing adhesive remnants is important, as this influences the selection and performance of bonding materials. Sayahpour et al[30] introduced a more standardized and quantitative approach, improving the reliability of ARI assessments. In our study, the conventional ARI index was used, as it remains the most common method in in vitro orthodontic research, although its inherent limitations should be acknowledged.

One study divided 96 extracted human maxillary premolars into four groups based on the type of curing light and exposure time. The halogen light group was cured for 20 and 40 seconds, while the LED light group was cured for 5 and 10 seconds.[31] The bond strength values showed significant differences between the groups, and the researchers recommended a curing time of 20 seconds for halogen and 5 seconds for LED light sources for orthodontic bracket bonding.[31]

Another study classified the samples into six groups according to the curing device and exposure duration. The LED group (Ortholux; 3M-Unitek) was cured for 5, 10, and 15 seconds, and the PAC group (Apollo 95E; DenMed Technologies) was cured for 3, 6, and 9 seconds. Bond strength values in the LED 5- and 10-second groups were statistically equivalent to those in the PAC 9-second group.[9]

Di Nicoló et al[32] evaluated the bond strength of APC brackets using QTH and LED systems. QHT was used for 20 seconds, and LED for 10 seconds. No significant difference was found, leading the authors to suggest that 10-second LED curing is sufficient while reducing chairside time.

In another study, Gomes et al[33] bonded 100 metal brackets to the buccal surfaces of human premolars using Transbond XT adhesive. The samples were randomly divided into five groups based on curing duration (2, 4, 6, 8, and 10 seconds; n=20) and were cured using an LED device with an intensity of 1600 mW/cm². Bond strength decreased when exposure time was reduced below 10 seconds. In contrast, Oz et al[14] demonstrated that adequate bracket bonding can be achieved with as little as 10 seconds of light curing using the Elipar LED, and 3 seconds using the VALO LED, without compromising bond safety.

The variability among studies may be mainly attributed to differences in the type of curing device, exposure duration, and light intensity. While some studies used conventional halogen or QTH units with longer curing times, others employed high-intensity LED or PAC systems capable of achieving sufficient polymerization in shorter periods. These variations in light output characteristics and total energy delivered may account for the inconsistent findings among studies on the optimal curing protocol for orthodontic bonding.

In the present study, the highest mean bond strength was observed in the group cured at standard power mode (1200 mW/cm²) for 1 × 10 seconds, while the lowest mean bond strength was found in the group cured at quadrant high power mode (3200 mW/cm²) for 2 × 3 seconds. However,

the differences in bond strength among the groups were not statistically significant. This lack of significant difference may be attributed to the similar total energy density delivered by all curing protocols, which ensured adequate polymerization across groups despite variations in light intensity and exposure duration. Moreover, the adhesive used in this study (APC Flash-Free) incorporates a highly efficient photoinitiator system, likely reducing the influence of variations in light-curing parameters. Conversely, another study reported that increasing both the light curing time and intensity positively influences the shear bond strength of orthodontic brackets, as well as the compressive strength of orthodontic adhesives.[13] However, such effects are likely to occur only when the total energy delivered falls below the polymerization threshold of the resin. In the present study, since all tested settings provided sufficient radiant exposure, the curing efficiency may have reached a plateau, resulting in similar bond strength values among groups. The curing time can be shortened to save time and improve patient comfort; however, this must be accompanied by an increase in light curing intensity in order to maintain the total energy required for adequate polymerization.[34]

Adhesive Remnant Index (ARI) scores are commonly used in the comparison of adhesive materials and in identifying differences between them.[35] Gupta et al[31] reported that the light-curing method did not influence ARI scores, and the most frequently observed score was 2. Another study also showed that the light-curing method had no effect on ARI scores, and the most common score was 3.[9] In a separate study, no significant difference was found in ARI scores between groups.[32] Gomes et al[33] stated that the weakest adhesive bond occurred at the bracket–adhesive interface. Oz et al[14] demonstrated that, following debonding, the majority of adhesive remained on the bracket bases, suggesting that the bond strength at the enamel–adhesive interface is lower than at the bracket–adhesive interface. No significant differences in ARI scores were observed between the groups.

In the current study, complete adhesive coverage on the tooth surface was observed in 55% of the teeth in the group cured under standard power mode using an LED curing unit. This rate was 40% in the group cured under high power mode and 30% in the group cured under quadrant high power mode. Although the standard power mode group showed the highest adhesive retention on the enamel surface, the differences between the groups were not statistically significant. This may indicate that, once sufficient polymerization is achieved, further increases in light intensity or reductions in curing duration do not alter the mode of bond failure. Additionally, the relatively uniform ARI distribution among groups supports the notion that the bonding interface strength was balanced between enamel and bracket sides, possibly due to the uniform adhesive layer thickness provided by the APC Flash-Free system. This standardized adhesive application may have contributed to the observed similarity in ARI score distribution, minimizing differences between curing modes.

Limitations

As this study was conducted under in vitro conditions, it should be supported by randomized controlled clinical trials. Multicenter, large-scale studies that include a variety of curing devices can provide clearer insights into the effect of LED curing units and their modes on bracket-tooth adhesion and how this effect translates into clinical outcomes. Another limitation of the present study is that, during thermocycling, other intraoral conditions, such as saliva, pH variations, and masticatory forces, were not simulated. Moreover, the study relied solely on visual ARI scoring without SEM analysis. The inclusion of SEM imaging could have provided detailed information about the curing modes and adhesive remnants, especially considering that there were no significant differences in ARI scores. Additionally, the study did not include a detailed failure mode classification (e.g., enamel vs. bracket base), nor were the degrees of conversion (DC%) of the resin or microleakage evaluations performed. Although these analyses could have provided a more comprehensive understanding of the adhesive interface, they were beyond the scope of the present investigation and are recommended for future research.

Future studies should incorporate a standardized bracket-seating force (e.g., using a force gauge) and record the light-tip distance and angulation to reduce potential variability in bond strength and polymerization.

CONCLUSION

There was no observed relationship between the bond strength at the bracket-tooth interface and the application modes of the LED curing unit. The application modes also did not produce a significant effect on ARI scores.

All tested modes showed comparable outcomes under in vitro conditions. Although the high-power mode allows shorter polymerization durations, its clinical applicability should be confirmed through further clinical or in vivo investigations.

Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author.

Artificial Intelligence Usage Statement: The authors declared that no Artificial Intelligence Tool was used in the preparation of the manuscript.

Ethics Committee Approval: Ethical committee approval was received from the Ethics Committee of Sivas Cumhuriyet University (Approval no: 2022-02/30, Date: February 16, 2022).

Informed Consent: Ethical approval and informed consent were not required for this study, as no human participants, human data, or animal subjects were involved.

Peer-review: Externally peer-reviewed.

Author Contributions: Concept - M.V.A., Z.Ç.B.; Design - M.V.A., Z.Ç.B.; Supervision - M.V.A., Z.Ç.B.; Resources - M.V.A., Z.Ç.B.; Materials - M.V.A.; Data Collection and/or Processing - M.V.A.; Analysis and/or Interpretation - M.V.A.,Z.Ç.B.; Literature Search - M.V.A., Z.Ç.B.; Writing Manuscript - Z.Ç.B.; Critical Review - M.V.A., Z.Ç.B.

Declaration of Interests: The authors have no conflicts of interest to declare.

Funding: The authors declared that this study has received no financial support.

REFERENCES

1. Powers JM, Kim HB, Turner DS, eds. Orthodontic adhesives and bond strength testing. *Semin Orthod*. 1997;3(3):147-156. [CrossRef]
2. Osorio R, Toledano M, Garcia-Godoy F. Bracket bonding with 15- or 60-second etching and adhesive remaining on enamel after debonding. *Angle Orthod*. 1999;69(1):45-48. [CrossRef]
3. Esmaeili B, Safarcherati H, Vaezi A. Hardness evaluation of composite resins cured with QTH and LED. *J Dent Res Dent Clin Dent Prospects*. 2014;8(1):40-44. [CrossRef]
4. Chaukse A, Dubey R, Agrawal N, et al. A review of orthodontic curing lights. *Int J Sci*. 2013;4(1):40-44.
5. González-Serrano C, Baena E, Fuentes M-V, et al. Shear bond strength of a flash-free orthodontic adhesive system after thermal aging procedure. *J Clin Exp Dent*. 2019;11(2):e154-e161. [CrossRef]
6. Kim J, Kanavakis G, Finkelman MD, et al. Microleakage under ceramic flash-free orthodontic brackets after thermal cycling. *Angle Orthod*. 2016;86(6):905-908. [CrossRef]
7. Lee M, Kanavakis G. Comparison of shear bond strength and bonding time of a novel flash-free bonding system. *Angle Orthod*. 2016;86(2):265-270. [CrossRef]
8. Reicheneder CA, Gedrange T, Lange A, et al. Shear and tensile bond strength comparison of various contemporary orthodontic adhesive systems: an in-vitro study. *Am J Orthod Dentofacial Orthop*. 2009;135(4):422.e1-6; discussion 422. [CrossRef]
9. Dall'Igna CM, Marchioro EM, Spohr AM, et al. Effect of curing time on the bond strength of a bracket-bonding system cured with a light-emitting diode or plasma arc light. *Eur J Orthod*. 2011;33(1):55-59. [CrossRef]
10. Alkhudhairy FI. The effect of curing intensity on mechanical properties of different bulk-fill composite resins. *Clin Cosmet Investig Dent*. 2017;9:1-6. [CrossRef]
11. Amato PAF, Martins RP, dos Santos Cruz CA, et al. Time reduction of light curing: influence on conversion degree and microhardness of orthodontic composites. *Am J Orthod Dentofacial Orthop*. 2014;146(1):40-46. [CrossRef]
12. Øgaard B, Fjeld M. The enamel surface and bonding in orthodontics. *Semin Orthod*. 2010;16(1):37-48. [CrossRef]
13. Mohammed OK, Younis MT, Dawood AE. The effect of light curing time and intensity on the bond strength and fracture resistance of orthodontic adhesive. *J Dent Res Dent Clin Dent Prospects*. 2023;17(1):23-27. [CrossRef]
14. Oz AA, Oz AZ, Arici S. In-vitro bond strengths and clinical failure rates of metal brackets bonded with different light-emitting diode units and curing times. *Am J Orthod Dentofacial Orthop*. 2016;149(2):212-216. [CrossRef]
15. Garma NMJ. The effect of light intensity and curing time of light-emitting diode on shear bond strength using different types of bracket materials. *Braz Dent J*. 2012;24(2):132-138.
16. Suresh K, Chandrashekara S. Sample size estimation and power analysis for clinical research studies. *J Hum Reprod Sci*. 2012;5(1):7-13. [CrossRef]
17. Katırcıoğlu A, Büyükbayraktar Z. Evaluation of the shear bond strength of light-cured and self-cured orthodontic adhesives. Forum Ortodontyczne; vol 18(1); 2022:18-23.
18. Årtun J, Bergland S. Clinical trials with crystal growth conditioning as an alternative to acid-etch enamel pretreatment. *Am J Orthod*. 1984;85(4):333-340. [CrossRef]
19. Saito H, Miyagawa Y, Endo T. Effects of plastic bracket primer on the shear bond strengths of orthodontic brackets. *J Dent Sci*. 2021;16(1):424-430. [CrossRef]
20. Marc M-G, Bazert C, Attal J-P. Bond strength of pre-coated flash-free adhesive ceramic brackets. An in vitro comparative study on the second mandibular premolars. *Int Orthod*. 2018;16(3):425-439. [CrossRef]
21. Bani AA, Tuncer BB, Tuncer C. Pulp chamber temperature changes during orthodontic bonding-an in vitro study. *Aust Orthod J*. 2021;37(2):157-164.
22. Türkkahraman H, Küçükeşmen HC. Orthodontic bracket shear bond strengths produced by two high-power light-emitting diode modes and halogen light. *Angle Orthod*. 2005;75(5):854-857. [CrossRef]
23. Billoo MS, Khan MAK, Khalid T, et al. Effect of storage medium of extracted human teeth on the result of in vitro studies – A scoping review. *Biomater Investig Dent*. 2025;12:44183. [CrossRef]
24. Haller B, Hofmann N, Klaiber B, et al. Effect of storage media on microleakage of five dentin bonding agents. *Dent Mater*. 1993;9(3):191-197. [CrossRef]
25. Aydın B, Pamir T, Baltaci A, et al. Effect of storage solutions on microhardness of crown enamel and dentin. *Eur J Dent*. 2015;9(2):262-266. [CrossRef]
26. Kiryk J, Matys J, Nikodem A, et al. The effect of er: :YAG laser on a shear bond strength value of orthodontic brackets to enamel-A preliminary study. *Materials (Basel)*. 2021;14(9):2093. [CrossRef]
27. Khan S, Verma SK, Maheshwari S. Effect of acid etching on bond strength of nanoionomer as an orthodontic bonding adhesive. *J Orthod Sci*. 2015;4(4):113-117. [CrossRef]
28. Wong J, Tsujimoto A, Fischer NG, et al. Enamel etching for universal adhesives: examination of enamel etching protocols for optimization of bonding effectiveness. *Oper Dent*. 2020;45(1):80-91. [CrossRef]
29. Zafar MS, Ahmed N. The effects of acid etching time on surface mechanical properties of dental hard tissues. *Dent Mater J*. 2015;34(3):315-320. [CrossRef]
30. Sayahpour B, Buehling S, Kopp S, et al. Reliability of qualitative and quantitative assessment of adhesive remnants after debonding of ceramic brackets bonded with Transbond™XT on human molar teeth: an in vitro study. *Int Orthod*. 2022;20(4):100680. [CrossRef]
31. Gupta SP, Shrestha BK. Shear bond strength of a bracket-bonding system cured with a light-emitting diode or halogen-based

light-curing unit at various polymerization times. *Clin Cosmet Investig Dent*;10:61-67. [CrossRef]
32. Di Nicoló R, Araujo MAM, Alves LAC, et al. Shear bond strength of orthodontic brackets bonded using halogen light and light-emitting diode at different debond times. *Braz Oral Res*. 2010;24(1):64-69. [CrossRef]
33. Gomes P, Portugal J, Jardim L. Effect of high-powered LED-curing exposure time on orthodontic bracket shear bond strength. *Rev Port Estomatol Med Dent Cir Maxilofac*. 2014; 55(2):78-82. [CrossRef]
34. Leprince JG, Palin WM, Hadis MA, et al. Progress in dimethacrylate-based dental composite technology and curing efficiency. *Dent Mater*. 2013;29(2):139-156. [CrossRef]
35. Kechagia A, Zinelis S, Pandis N, et al. The effect of orthodontic adhesive and bracket-base design in adhesive remnant index on enamel. *J World Fed Orthod*. 2015;4(1):18-22. [CrossRef]