Original Article

Comparison of the Adhesive Remnant Index and Shear Bond Strength of Different Metal Bracket Bases on Artificially Aged Human Teeth: An *In vitro* Study

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Abstract

Aim: Bond failure can compromise the clinical efficacy and duration of orthodontic treatment. A decemented bracket can lengthen the course of treatment by about 0.6 months. This study aimed to compare the adhesive remnant index (ARI) and shear bond strength of different metal bracket bases on artificially aged human teeth. **Materials and Methods:** In this experimental *in vitro*, prospective, cross-sectional study, thirty-six human premolars were cemented with three types of metal bracket base designs: Group 1 had a laser-structured base, Group 2 had a mesh base, and Group 3 had a base with retention grooves. All groups were bonded with Transbond XT light-curing resin. Shear strength testing was performed, and the ARI was evaluated. The parametric one-factor analysis of variance test and Tukey's *post hoc* test were used for the comparison of shear bond strength, and the effect size was also evaluated with eta squared. In addition, the Kruskal–Wallis test was used to compare the ARI of the three groups on an ordinal scale. All statistics were set at a significance of $P < 0.05$. **Results:** The ARI scores did not exhibit any statistically significant differences ($P = 0.163$). Nevertheless, the three groups exhibited statistically significant differences in shear bond strength, with an effect size of 69% ($P < 0.001$). The mesh base bracket had the lowest average (9.9 ± 2.6 MPa) ($P < 0.001$), while the laser-structured base bracket had the greatest average (19.1 ± 3.0 MPa) ($P = 0.006$). **Conclusion:** The variation in shear bond strength was influenced by 69% due to the type of the metal bracket base used. Laser-structured and mesh-based brackets had the highest and lowest shear strength, respectively. All bases left a similar ARI on the tooth enamel.

Keywords: *Dental bonding, fixed, orthodontic appliances, orthodontic brackets, orthodontics, shear strength*

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Introduction

Fixed appliance manufacturers are working to improve the bond strength between brackets and enamel.[1,2] The success of a fixed appliance orthodontic treatment mostly hinges on each component remaining

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stable on the enamel surface during the course of the therapy.[1] It is therefore imperative that the brackets remain attached to the teeth until the conclusion of the treatment in order to achieve the desired results within the specified number of sessions and working time.[2]

During orthodontic treatment, the bracket must be capable of withstanding occlusal forces, mastication, and the traction forces applied by the archwire. Additionally, the bracket must be designed in such a way that it can be removed promptly following treatment without causing damage to the enamel.[3]

Bracket debonding has been recognized as one of the factors affecting the clinical efficacy and duration of orthodontic treatment, along with patient compliance and treatment variations and approaches. A debonded bracket can add roughly 0.6 months to the length of treatment, which means the patient will spend more time in the chair and incur higher costs.[1,4,5]

Variables such as the type of polymerization, adhesives utilized, tooth surface, and base shape affect the adhesive strength of the bracket.[6,7] In the case of metal brackets, the bond to tooth enamel is based on the principle of mechanical retention. For this reason, the bracket base's retentive design is crucial.[7] Additionally, factors such as the size, retention pattern, surface treatment, and shape of the base should also be considered.[6-8]

There are several types of bases available to guarantee adequate mechanical retention and aid in the adhesion of brackets to dental enamel. These include waffle bases, laser-structured bases, photo-etched, welded metal bracket bases, integral bases that can be drilled, mesh foil, and slotted retention. However, several bracket base designs have been shown to possess variable levels of binding strength.[8,9] Hence, while selecting a bracket system, the clinician must consider the patient's requirements since the fundamental qualities might influence the effectiveness of the adhesive and mechanical interlock.[10,11]

The adhesive remnant index is employed for the categorization of the site of bond failure and for detailed information regarding the adhesive bond between the bracket base and the tooth surface.[6,11]

In orthodontics, it is essential to simulate oral conditions prior to mechanical testing. Therefore, applying 10,000 thermal cycles is advantageous in simulating 1 year of clinical aging.[12,13]

Several studies[6-10] have assessed the shear bond strength and ARI of brackets produced using diverse materials and immediate techniques. However, currently, there is little evidence on the impact of thermocycling on simulating long-term clinical outcomes. Therefore, it is important to consider, as there are alternating stresses at the interface of the materials and potential adhesive loss due to differences in thermal expansion coefficients, which may lead to premature debonding of the brackets.[5,13] Furthermore, it is of interest not only to compare which brackets perform better in shear bond strength but also to statistically measure the size of the effect.

The objective of the study was to assess and evaluate the ARI and shear bond strength of three distinct metal bracket bases on human teeth in a controlled laboratory setting, following exposure to simulated aging conditions. The study examined two null hypotheses. The first null hypothesis posited that there would be no substantial disparities in the ARI among the three distinct metal bracket bases. The second null hypothesis posited that there would be no statistically significant variations in shear bond strength across the three distinct metal bracket bases.

Materials and Methods

Study delimitation and design

This experimental *in vitro* research was conducted from January to March 2020 at the Inca Garcilaso de la Vega University and the Certified High Technology Laboratory (ISO/IEC Standard: 17025), located in the Peruvian capital. The study was reported using the CRIS Guidelines.[14]

Calculation of sample size

A total of 36 premolars from human subjects were excised 3 months prior to the experiment for orthodontic reasons. The teeth used for the study were selected based on their undamaged outer surfaces, lack of tooth decay, fractures, dental fillings, and discoloration. The sample size for each group was 12 teeth, computed using the analysis of variance (ANOVA) test procedure with the statistical program G*Power 3.1.9.7. The significance threshold was established at $\alpha = 0.05$, with a statistical power of $1 - \beta = 0.80$ and an effect size of 0.56. The parameters were derived from a prior pilot research, which included five samples in each group. The three groups were created through a straightforward random allocation: Group A comprised Discovery® Smart Brackets with a laser-structured base (Dentaurum, Ispringen, Germany), Group B comprised Mini Master® Series Brackets with a mesh base (American Orthodontics, Sheboygan, NY, USA), and Group C comprised Roth Max Brackets with a retention groove base (Morelli®, Sorocaba, SP, Brazil) [Figure 1].

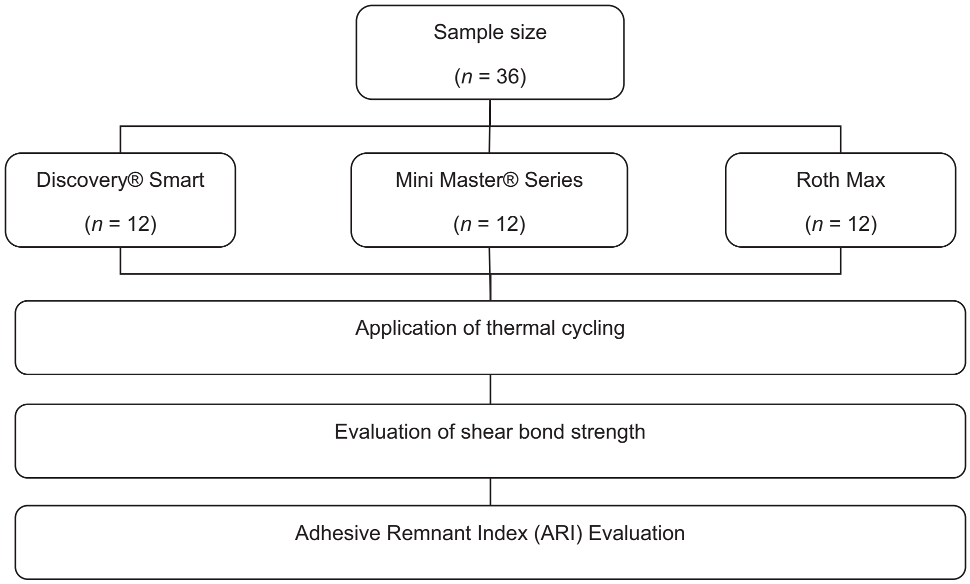

Figure 1: Random distribution of groups according to sample size

Sample preparation

In order to prevent dehydration and the growth of germs, the teeth were initially rinsed with water to remove any soft tissues and subsequently submerged in a 0.1% thymol solution for a duration of 1 week.[7,8] Afterward, the specimens were kept in distilled water until the investigation was carried out, with the water being replaced every week following the guidelines of ISO/TS11405:2015,[15] and not exceeding a storage period of 3 months.[16]

Mounting and prophylaxis of dental pieces

A Zeta plus heavy silicone condensation mold with an internal diameter of 30 mm and a length of 30 mm, manufactured by Zhermack in Badia Polesine, Italy, was utilized to pour three different types of dental stone: Vel-Mix™ type IV from Kerr Corporation in Orange, CA, USA; Fujirock® EP from GC America Inc. in Alsip, Illinois, USA; and Elite Stone from Zhermack in Badia Polesine, Italy. The roots of the teeth were vertically implanted up to 1 mm below the cementoenamel junction, resulting in the roots being enclosed within the stone. This was done to ensure that the crowns remained visible, making it easier to carry out surface treatment and attach brackets.[7,10,11] Each sample group was assigned different plaster colors: Group 1 (laser-structured brackets) was pink, Group 2 (brackets with mesh base) was blue, and Group 3 (brackets with retention groove base) was white. Prophylaxis was performed using a low-speed Micromotor EX-203C (NSK, Tokyo, Japan) and pumice.[7,8,11] The area was then rinsed thoroughly with water by using a triple syringe for 10 s and dried.[8]

Study group cementing protocol

The phosphoric acid etching gel Condac 37 (FGM, Joinville, Santa Catarina, Brazil) was used to treat the outer surface of the visible part of the tooth for 15 s. Subsequently, it was washed with water and allowed to dry naturally. A small layer of the Transbond™ XT primer (3M™ Unitek, Monrovia, CA, USA) was applied to the enamel and gently rubbed for 10 s. Next, the Transbond XT resin was applied to the bottom of the metal bracket using bracket holder tweezers.[6,17] The bracket was positioned in the center of the clinical crown and verified for accurate placement by using a bracket positioner (Morelli®, Sorocaba, SP, Brazil).[4] A dental explorer was used to remove the excess material. The resin polymerization was completed with the Valo Cordless® (Ultradent©, South Jordan, UT, USA) light-emitting diode light-curing unit at an intensity of 1000 mW/cm^2 for 10 s mesially and 10 s distally from the bracket.[7,8]

Shear bond strength and storage

The specimens were incubated in distilled water at a temperature of 37°C for a duration of 24 h.[6,7] A total of 10,000 thermocycles were conducted on the samples,[12] with temperatures ranging from 5°C to 55°C, prior to performing shear tests. The latter experiment was conducted by using a universal testing machine (CMT-5L, 7419, LG, Seoul, Korea) equipped with a 5000 Newton load cell. The crosshead speed was set at 0.75 mm/min. A force was exerted on the brackets in the occlusogingival direction by using a blade that created a force at the interface between the enamel and the bracket until the bracket became dislodged.[3,7] The highest load was measured in

Newton (N) and subsequently converted to megapascal (MPa) by dividing the force by the area enclosed by the brackets.[7,17] The Discovery® Smart, Mini Master® Series, and Roth Max brackets have bracket surface areas of 10.18, 10.01, and 11.32 mm², respectively.

ARI	Criteria
Score 0 	No adhesive left on the tooth
Score 1 	Less than half of the adhesive left on the tooth
Score 2 	More than half of the adhesive left on the tooth
Score 3 	All the adhesive left on the tooth with the mesh pattern visible

Figure 2: Adhesive remnant index and criteria

Adhesive remnant index evaluation

A stereomicroscope (Leica EZ4, Wetzlar, Germany) at 10x magnification after shear testing was used to observe the vestibular surface of the tooth enamel.[7,9,10] The failure mode scores were recorded in accordance with the original description provided by Artun and Bergland [Figures 2 and 3].[18]

Statistical analysis

The findings were processed using Statistical Package for Social Sciences version 28.0 (IBM Corp., Armonk, NY, USA), a statistical software. Descriptive statistics were employed to compute measures of central tendency, as well as measures of dispersion, for the three groups. The study employed inferential statistics to evaluate the normal distribution and homoscedasticity of the data. The Shapiro–Wilk and Levene tests were employed for this specific aim, correspondingly. Tukey's *post hoc* test and the parametric one-factor ANOVA test were used to compare the shear strength results. The effect magnitude was calculated using eta squared. The Kruskal–Wallis test was used to compare the three groups based on an ordinal scale for the ARI. The statistical assessments were performed using a significance level of $P < 0.05$.

Results

The laser-structured base brackets had a mean shear bond strength of 19.1 ± 3.0 MPa, while the mesh base brackets exhibited a mean shear bond strength of 9.9 ± 2.6 MPa. Furthermore, brackets with a retention

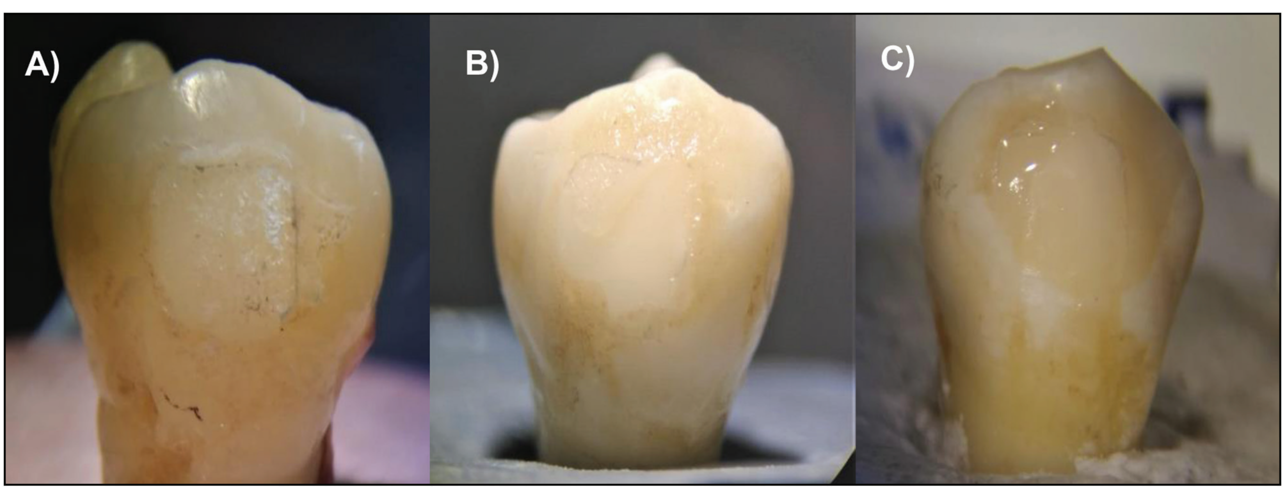

Figure 3: The adhesive remnant index left by the bracket bases after debonding, analyzed using the stereomicroscope. (A) Discovery® Smart laser-structured base, (B) Mini Master® Series mesh base, and (C) Roth Max® base brackets with retention grooves

Table 1: Descriptive analysis and comparison of shear bond strength (MPa) between the study groups

Brackets	*n*	Mean	SD	SE	95% CI		Min	Max	*P**	*P***	*P****	η^2
					LL	UL						
Laser-structured base	12	19.16^A	3.06	0.88	17.21	21.10	13.33	22.95	0.106	0.666	<0.001	0.69
Mesh base	12	9.93^B	2.62	0.76	8.27	11.60	6.94	15.68	0.212			
Base with retaining grooves	12	15.51^C	2.29	0.66	14.06	16.97	11.63	18.91	0.492			

*Based on the Shapiro–Wilk normality test ($P > 0.05$, normal distribution).

**Based on Levene's homoscedasticity test ($P > 0.05$, homogeneous variances).

***Based on one-factor ANOVA test (**$P < 0.05$, significant differences). ^{A,B}Different letters in the same column as the mean indicated significant differences ($P < 0.05$) based on Tukey's *post hoc*. η^2 = test effect size, *n* = sample size, SD = standard deviation, SE = standard error, 95% CI = 95% confidence interval, LL = lower limit, UL = upper limit, Min = minimum value, Max = maximum value

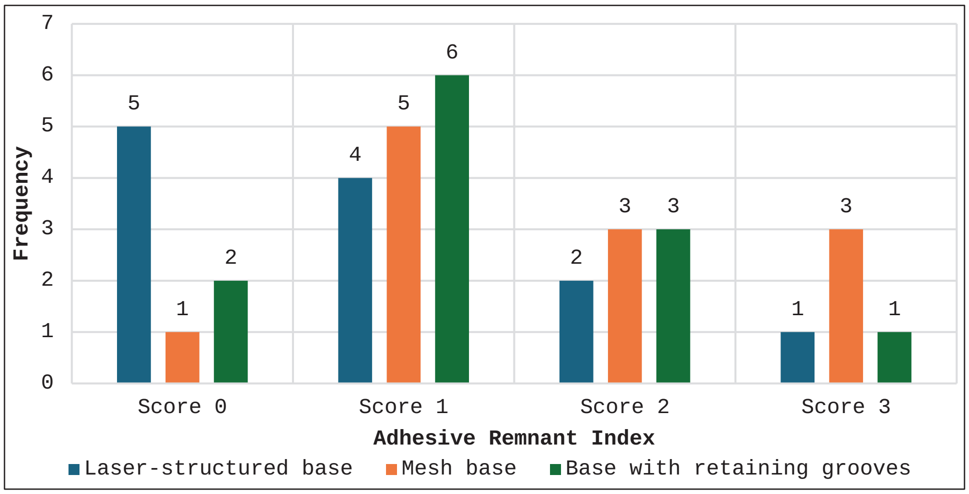

Figure 4: Absolute frequency of the adhesive remnant index according to the metal bracket base used

Table 2: Comparison of the adhesive remnant index according to the type of the bracket used

Bracket	*n*	Mean	Median	IQR	H	**P*
Laser-structured base	12	0.92	1.0	2	3.63	0.163
Mesh base	12	1.67	1.5	2		
Base with retaining grooves	12	1.25	1.0	1		

*Based on Kruskal–Wallis *H* test; significant differences ($P < 0.05$). *H* = statistic, *n* = sample size, IQR = interquartile range

groove base exhibited a mean shear bond strength of 15.5 ± 2.2 MPa. According to the findings of the statistical analysis, the shear bond strength of the laser-structured base brackets was substantially greater than that of the retention slotted base brackets ($P = 0.006$). Furthermore, it is worth noting that both kinds of brackets exhibited superior shear bond strength in comparison to mesh-based brackets, with statistical significance ($P < 0.001$ and $P < 0.001$). Finally, it was found that the kind of metal base of the bracket explained 69% of the difference in shear bond strength, which was measured in MPa on the bracket [Table 1].

Out of the 12 samples per group, it was observed that 41.7% of the brackets with a laser-structured base and the same percentage of brackets with a mesh base had an ARI score of 0 and 1, respectively. Additionally, 50.0% of the brackets with retention grooves had an ARI score of 1. The findings showed that there was no statistically significant difference in the ARI across the three distinct bracket bases [Table 2 and Figure 4].

Discussion

In a laboratory environment under controlled conditions throughout the research, the purpose of the study was to assess the shear bond strength and remnant adhesive index of three distinct metal bracket base designs on human teeth after 10,000 thermocycles. This was done in order to ascertain the ultimate results of the inquiry. Because the remnant adhesiveness index did not reveal any significant differences between the three distinct metal bracket bases, the initial null hypothesis was not rejected. On the other hand, when the three different designs of metal bracket bases were analyzed, it was discovered that there were significant variances in the shear bond strength. Therefore, the second null hypothesis was rejected as a valid explanation.

It is possible that the diverse base designs are responsible for the considerable differences in shear bond strength observed across the research groups. According to the results of prior research studies carried out by Dholakiya *et al.*,[19] Castillo *et al.*,[20] Rajesh *et al.*,[21] and Corahua-Raymi *et al.*,[22] these findings are in agreement with the findings. Despite this, Molina *et al.*[23] and Bishara *et al.*[24] found no significant differences across the study groups examined. This may be attributed to the use of a variety of adhesive methods as well as a variety of metal bases, including double mesh bases and horizontal groove bases, among others.

In a previous study, Roth Max and Discovery® Smart presented similar shear strength values without significant differences between them, when thermal cycling was not applied. However, when thermal cycling was applied in the present study, the three groups showed differences among themselves, with Discovery® Smart obtaining the highest values. The bracket system consists of a well-built foundation and a strong Nd:YAG laser that liquefies and melts metal to create hole retentions. The base design provides both macro- and micro-retention, resulting in superior bond strength.[3] Research suggests that laser irradiation on the bracket surface enhances adhesive strength compared to other methods.[21,25]

The investigation revealed that the shear strength of Roth Max was markedly more than that of the Mini Master® series, but it was notably lower than that of the Discovery® Smart. The retention groove base of Roth Max is micro-sanded, resulting in significant retention. Additionally, it has tiny pins that optimize bonding and anchoring area to the adhesive.[26] The superior performance of Roth Max can be due to the increased bond strength of the metal brackets, which is obtained by sandblasting, silanization of the bracket base, and chemical treatment.[6] The Mini Master® series had the lowest shear strength. This bracket has an etched foil base that is photochemically etched and has an 80-gage soldered mesh on it, creating porosity that aids in retention.[26] Nevertheless, air entrapment caused by the solder on the Mini Master® series base may result in voids beneath the solder points. This can lead to decreased air retention and potentially cause the adhesive to inadequately penetrate the area, resulting in marginal leakage and possible bond failure.[21,23] It has been suggested that integral bases are more retentive than welded wire mesh bases.[27,28] This may explain why Discovery® Smart and Roth Max, which are integral bases, achieved higher adhesion values compared to Mini Master®.

When evaluating the statistical differences among the three types of brackets, it was observed that the type of metal base accounted for 69% of the variation in shear bond strength in MPa. Moreira *et al.*[25] reported that different bracket base treatments lead to different bond strengths on enamel, with variations of up to 26%. It is important to note that the research by Moreira *et al.*[25] did not include thermal cycling. The area and curvature of the bracket base are variables influencing bond strength. Given the 69% variation found in this study, which is higher than that found by Moreira *et al.*,[25] it is possible that greater differences could be found between the different types of metal bases considered in a clinical setting. It is important to note that thermal cycling only simulates oral conditions to a limited extent.

According to Reynolds,[28] the optimal strength range is between 5.9 and 7.9 MPa. Diedrich[29] proposes a pressure range of 5–10 MPa, although Morales *et al.*[30] and Agarwal *et al.*[3] propose a narrower range of 6–8 MPa. Values beyond 13–14 MPa increase the probability of enamel fracture. This is due to the surpassing of the cohesive forces inside the adamantine structure.[9] The Mini Master® series was found to be within the recognized clinical values in this investigation. However, the Discovery® Smart and Roth Max systems exceeded the ideal range. It is important to note that an artificial aging process of 10,000 thermal cycles was performed, which is equivalent to 1 year of clinical time.[12,13] Therefore, it can be assumed that these systems may increase the risk of enamel fracture. However, it is important to note that the simulated temperature changes[12,13] may not accurately reflect *in vivo* bond strengths. Studies have demonstrated that binding strengths achieved in laboratory settings (*in vitro*) are often greater than those observed in living organisms (*in vivo*).[6,31] This is because the presence of moisture in the oral environment can greatly diminish the effectiveness of adhesion.[5] Pickett *et al.*[31] compared the findings obtained in laboratory settings (*in vitro*) and those obtained in living organisms (*in vivo*). They discovered that the bond strengths after orthodontic treatment in living organisms (5.5 MPa) were much lower than the bond strengths observed in laboratory settings (12.8 MPa). The prolonged exposure of dental materials to acids, saliva, patient abrasion, and masticatory force in the oral cavity might explain the significant deterioration of the bond.

The study's ARI scores indicate that Discovery® Smart ranged from 0 to 1, while Roth Max and Mini Master® Series both scored 1. ARI is an often used indicator of the quantity of adhesive left on the tooth surface following debonding.[13] An orthodontic biomaterial should aim for a mixed or cohesive bond (ARI score 1 or 2).[13] According to research, a score of "0" is typically linked to greater enamel damage. This evaluation leads to increased stress on the enamel during decementation, resulting in more damage to the enamel surface.[6,13] Molina *et al.*[23] suggests that achieving high ARI scores is ideal for maintaining enamel integrity and reducing the occurrence of enamel fractures. Removal of residual adhesive should be performed with special drills that do not damage the enamel. According to Henkin *et al.*,[32] surface conditioning and debonding methods can also have a significant impact on the likelihood of enamel fracture; therefore, bond strength is not the only factor. Despite the results, there were no significant differences among the three study groups. Therefore, it can be assumed that the stress generated during debonding is similar in all three groups. These findings contradict those of Dholakiya *et al.*[19] and Castillo *et al.*,[20] who found differences among their study groups. However, it should be noted that thermal cycling was not used in either study. It is important to evaluate the results of ARI carefully, as they are subjective.[21]

After 10,000 cycles of thermocycling, differences were found in the shear bond strength of the base types, but not in the remnant adhesive, as all three types of brackets left a similar amount after debonding. This was similar to that found by Alsulaimani *et al.*,[33] who reported that thermocycling did not affect ARI scores, even though they applied 5000 thermocycles.

An important aspect of the study was the incorporation of artificial aging in assessing the long-term clinical outcomes.[5] The 10,000 thermal cycles provided corresponded to the aging process that would typically occur over the course of a year in a clinical setting.[12,13] Moreover, the identical operator performed all procedures. While placing the brackets, the adhesive layer was thin and consistent, and any extra glue was removed without moving the bracket out of place. The study utilized the Transbond XT adhesive technology. Due to its exceptional adhesive properties,[10,19] this product is frequently employed in orthodontics. To exclude any confounding factors, all groups underwent light curing using a same methodology, thus ensuring that any variations in bond strength values were purely attributable to disparities in bracket base design.

It is critical to recognize the limitations of this study. The results of this *in vitro* thermal cycling study may not be directly applicable to a clinical setting due to various external factors that may influence bond failure, such as moisture contamination of etched enamel, environmental exposure, type of malocclusion, appliance maintenance, trauma, and general diet.[22]

The importance of this work lies in the identification of the bracket base design that exhibits the greatest shear strength. This will enable dentists to select the bracket system that yields the best long-term clinical outcomes, preventing debonding and avoiding unnecessary treatment time extension.[6] It would be recommended that future research takes into account the size and shape of the bracket base, given that studies have demonstrated that larger base sizes may result in greater bond strength compared to smaller base sizes. In addition, the shape of the bracket base may also have an effect on shear strength, as it may allow for variable force distribution.[5,33] Furthermore, it would be recommended that randomized controlled clinical trials be conducted to evaluate the bond strength and ARI of metal brackets with different base types.[34]

Conclusion

The type of metal bracket base has a substantial effect on the variation in shear bond strength by 69% after artificial aging in this *in vitro* study. The laser-structured base brackets exhibited significantly higher shear bond strength than the retention groove base brackets, while the latter exhibited significantly higher shear strength than the mesh base brackets. Finally, it was observed that all three types of brackets left a similar amount of adhesive remnant on the tooth enamel when debonded.

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Conflicts of interest

There are no conflicts of interest.

Author contributions

They conceived the research idea (LCG and CCR), elaborated the manuscript (LCG, CCR, RAA, LCR, JHE, and MLC), collected and tabulated the information (CCR and RAA), carried out the bibliographic search (LCG, MLC, JHE, and LCR), interpreted the statistical results (CCR and JHE), helped in the development of the discussion (LCG, LCR, and CCR), and performed the critical review of the manuscript (CCR, LCG, and MLC). All authors approved the final version of the manuscript.

Ethical policy and Institutional Review Board statement

The present study respected the bioethical principles for medical research with human beings found in the Declaration of Helsinki. This study was exempted from review by the ethics committee of the Inca Garcilaso de la Vega University because it was an *in vitro* study. The teeth used were voluntarily donated and extracted for orthodontic or prosthetic reasons, with prior informed consent.

Patient declaration of consent

Not applicable.

Data availability statement

The data that support the study results are available from the author (Dr. Luis Cervantes-Ganoza, e-mail: luiscervantesganoza@outlook.com) on request.

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