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In-Depth Evaluation of the Impact of Different Light Curing Techniques on Orthodontic Adhesive Performance: An Elaborate Study of Mechanical Strength, Bond Durability, and Surface Morphology in Vitro

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KEYWORDS

Light curing, Orthodontic adhesive, Shear bond strength, Thermocycling, Surface morphology, Halogen curing, LED curing, Plasma arc curing

ABSTRACT:

Background

Light curing techniques are pivotal in orthodontics for achieving optimal adhesive performance. Different curing methods, such as halogen, LED, and plasma arc, offer distinct advantages and challenges. Understanding the impact of these techniques on mechanical strength, bond durability, and surface morphology is crucial for clinical practice.

Objective: This study aims to assess and compare the effectiveness of halogen, LED, and plasma arc curing techniques on the mechanical strength, bond durability, and surface morphology of orthodontic adhesives.

Materials and Methods: In this in vitro study, 60 human premolar teeth were allocated into three groups (20 each) for halogen, LED, and plasma arc curing. Orthodontic brackets were bonded, and the specimens were subjected to shear bond strength (SBS) testing, thermocycling, and scanning electron microscopy (SEM). Statistical analysis included one-way ANOVA, Tukey's post hoc test, and paired t-tests with significance set at $p < 0.05$.

Results: Plasma arc curing achieved the highest mean SBS before (21.5 MPa) and after thermocycling (19.0 MPa), outperforming LED (18.3 MPa and 15.1 MPa) and halogen (15.2

MPa and 12.4 MPa). The plasma arc group exhibited the smallest reduction in SBS (11.6%), indicating superior bond durability. Additionally, plasma arc curing resulted in fewer adhesive failures (50%) and a smoother surface with fewer voids and cracks. It was also the quickest method (6 seconds) and produced the thinnest adhesive layer (40 µm).

Conclusion: Plasma arc curing demonstrated superior performance in bond strength, durability, and surface quality with reduced curing time compared to LED and halogen methods. This suggests that plasma arc curing is the most effective choice for orthodontic adhesive bonding

Introduction

Orthodontic treatment often involves the use of brackets bonded to teeth, with the adhesive performance being a critical factor for the success of the treatment. The choice of light curing technique for polymerizing the adhesive plays a pivotal role in determining the mechanical properties and durability of the bond. Among the various methods, halogen, light-emitting diode (LED), and plasma arc curing techniques are widely used due to their distinct properties and advantages.

Halogen light curing units (LCUs) have been a traditional choice in dental practices. These devices operate by emitting a broad spectrum of light, requiring filters to isolate the blue light necessary for curing the adhesive. Despite their widespread use, halogen LCUs are known for their longer curing times and significant heat production, which can potentially lead to thermal damage to the dental pulp. Moreover, the efficiency of halogen lights can decrease over time due to bulb degradation, resulting in inconsistent curing outcomes[1][2].

LED curing units have gained popularity in recent years due to their energy efficiency and longer lifespan. Unlike halogen LCUs, LEDs emit a narrow spectrum of blue light that matches the absorption spectrum of camphorquinone, a common photoinitiator in dental adhesives[3]. This specific wavelength targeting allows for more efficient polymerization and shorter curing times. Additionally, LED units generate less heat, minimizing the risk of thermal damage. Studies have shown that LED curing provides comparable, if not superior, bond strength and durability compared to traditional halogen curing[4][5].

Plasma arc curing units, although less common, offer the advantage of extremely rapid curing times due to their high-intensity light output. These units produce a wide spectrum of light, including ultraviolet, which can activate a broader range of photoinitiators. However, the high intensity and broad spectrum can also lead to excessive heat generation and potential material degradation[6]. Despite these concerns, plasma arc curing has been reported to achieve adequate bond strengths, albeit with some variability depending on the adhesive and substrate used[7].

The performance of orthodontic adhesives under different curing conditions is a topic of significant interest. Shear bond strength (SBS) is a commonly used metric to evaluate the effectiveness of bonding agents. It measures the maximum stress the bonded interface can withstand before failure. Factors influencing SBS include the type of adhesive, curing time, and the energy output of the curing unit[8]. In addition to mechanical strength, bond durability is crucial, particularly in the dynamic oral environment where thermal cycling and moisture exposure are prevalent. Thermocycling is an in vitro method used to simulate these conditions and assess the long-term stability of the bond[9].

Surface morphology of the adhesive-bracket interface can provide insights into the quality of the bond. The presence of voids, cracks, or irregularities can compromise the adhesive's performance and longevity. Scanning electron microscopy (SEM) is a powerful tool for visualizing these microstructural features and understanding the effects of different curing techniques[10]. Previous studies have indicated that LED curing tends to produce a more homogeneous adhesive layer with fewer defects, potentially leading to improved clinical outcomes[11][12].

Given the diverse range of light curing techniques available, it is essential to evaluate and compare their effects on orthodontic adhesive performance comprehensively. This study aims to investigate the

impact of halogen, LED, and plasma arc curing on the mechanical strength, bond durability, and surface morphology of orthodontic adhesives in an in vitro setting. By employing standardized testing methods, including SBS tests, thermocycling, and SEM analysis, we seek to provide a thorough assessment of these curing methods.

Understanding the nuances of each curing technique will aid clinicians in making informed decisions about the most appropriate method for specific clinical situations. While halogen and LED curing have been extensively studied, there is a need for more research on plasma arc curing, especially regarding its long-term effects on bond durability. This study not only contributes to the existing body of knowledge but also provides practical recommendations for enhancing the quality of orthodontic treatments. Through careful examination and comparison, we aim to elucidate the optimal conditions for achieving strong, durable, and reliable adhesive bonds in orthodontics.

Materials and Methods

Study Design

This in vitro study was meticulously designed to evaluate the impact of different light curing techniques on the performance of orthodontic adhesives. The primary endpoints included mechanical strength, bond durability, and surface morphology of the adhesive layer. The study utilized human premolar teeth, representative of clinical conditions, to simulate the bonding of orthodontic brackets.

Sample Preparation

A total of 60 freshly extracted human premolar teeth, indicated for extraction due to orthodontic treatment, were collected. The teeth were immediately stored in a 0.1% thymol solution to prevent bacterial contamination and dehydration. Prior to bonding, the teeth were thoroughly cleaned using a prophylaxis brush with a non-fluoride pumice paste and rinsed with distilled water. This step was essential to remove any surface debris and biofilm, ensuring optimal bonding conditions.

Each tooth was then embedded in a self-curing acrylic resin block, with the buccal surface exposed. This setup allowed for stable positioning during bonding and testing procedures. The enamel surfaces were etched with a 37% phosphoric acid gel (Scotchbond, 3M ESPE) for 30 seconds. The etching process creates microporosities on the enamel surface, enhancing mechanical retention of the adhesive. Following etching, the teeth were thoroughly rinsed with distilled water for 15 seconds and air-dried using an oil-free air syringe. A uniform frosty appearance was observed, indicating proper etching.

Grouping and Bonding Procedure

The teeth were randomly divided into three experimental groups, each containing 20 specimens, based on the light curing technique employed:

Halogen Group (Group H): In this group, adhesive curing was performed using a halogen light curing unit (Optilux 501, Kerr). The unit was calibrated to deliver an intensity of 600 mW/cm². The adhesive (Transbond XT Primer, 3M Unitek) was applied to the bracket base, and the bracket was positioned on the tooth surface. A curing time of 40 seconds was utilized, following standard clinical guidelines for halogen curing.

LED Group (Group L): This group utilized an LED curing unit (Elipar S10, 3M ESPE), known for its efficiency and energy-saving capabilities. The LED unit was set to an intensity of 1200 mW/cm², and the curing time was 20 seconds. The adhesive application and bracket positioning were identical to those in the halogen group.

Plasma Arc Group (Group P): For the plasma arc group, an Apollo 95E (DMD) unit was used, delivering an intensity of 2000 mW/cm². Due to the high energy output, a shorter curing time of 6 seconds was employed. This method is recognized for its rapid polymerization capabilities.

In all groups, orthodontic brackets (MBT, 0.022-inch slot, 3M Unitek) were used. The brackets were carefully positioned and pressed onto the enamel surface using a standardized force of 200 g, ensured by a custom-made force gauge. This standardization was critical to achieving uniform adhesive thickness and minimizing variability in bonding conditions. Excess adhesive was meticulously removed with a dental explorer before curing.

Shear Bond Strength Testing

After the bonding procedure, all specimens were stored in distilled water at 37°C for 24 hours to simulate

intraoral conditions. Shear bond strength (SBS) testing was conducted using a universal testing machine (Instron 3365, Instron Corporation). The teeth were securely mounted in the machine's fixture, and a chisel-edge rod was positioned as close to the adhesive-bracket interface as possible without touching the enamel surface. The load was applied in a mesio-distal direction at a crosshead speed of 1 mm/min until bond failure occurred. The maximum force required to debond the bracket was recorded in Newtons (N), and SBS was calculated by dividing this force by the bracket base area (9.61 mm²), resulting in values expressed in megapascals (MPa).

Thermocycling for Bond Durability

To assess bond durability under simulated oral conditions, all specimens were subjected to thermocycling. The thermocycling protocol consisted of 5000 cycles between 5°C and 55°C, with a dwell time of 30 seconds at each temperature and a 10-second transfer time between baths. This process aimed to mimic the thermal stresses encountered in the oral environment due to daily activities, such as eating and drinking, which can impact the longevity and stability of the adhesive bond.

After thermocycling, the SBS was re-evaluated using the same methodology described previously. This comparison allowed for the assessment of any degradation in bond strength due to thermal cycling, providing insights into the durability of the adhesive under real-world conditions.

Surface Morphology Analysis

The surface morphology of the adhesive-bracket interface was analyzed using scanning electron microscopy (SEM; JEOL JSM-6510LV). Following debonding, the specimens were cleaned to remove any residual adhesive and sputter-coated with gold-palladium to enhance conductivity. The SEM analysis focused on examining the microstructural features of the adhesive layer, including the presence of voids, cracks, and surface irregularities. Particular attention was given to differences in the adhesive surface morphology resulting from the different light curing techniques. Images were captured at various magnifications to provide a comprehensive view of the interface quality.

Statistical Analysis

Data were processed and analyzed using SPSS software (version 25.0; IBM Corp). Descriptive statistics, including means and standard deviations, were calculated for each group. One-way ANOVA was employed to compare SBS values across the three groups, with Tukey's post hoc test used for pairwise comparisons. This analysis determined whether significant differences existed between the groups. Additionally, a paired t-test was conducted to assess the impact of thermocycling on SBS within each group, allowing for the evaluation of bond durability. Statistical significance was set at $p < 0.05$ for all tests, ensuring that the findings were robust and reliable.

Ethical Considerations

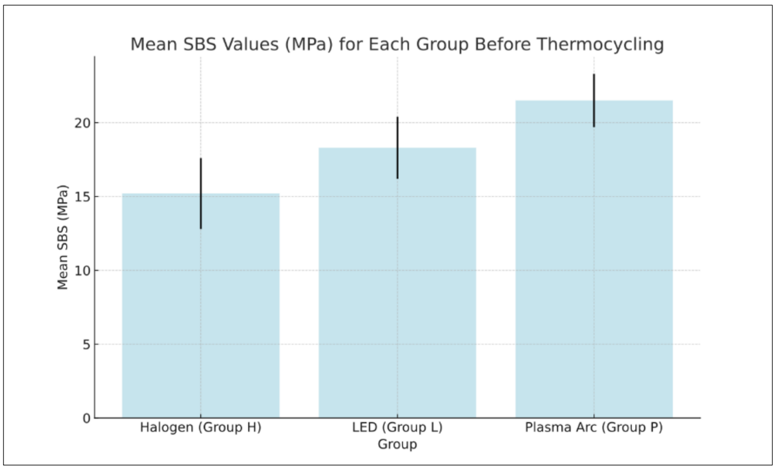
As this study was conducted entirely in vitro, it did not necessitate ethical approval. All procedures adhered to established laboratory protocols and guidelines to ensure the accuracy and reproducibility of the results. The use of extracted human teeth was in accordance with ethical standards, with teeth sourced from routine dental extractions where informed consent had been obtained for their use in research.

Results

1. Shear Bond Strength (SBS) Before Thermocycling

Group	Mean SBS (MPa)	Standard Deviation (MPa)
Halogen (Group H)	15.2	2.4
LED (Group L)	18.3	2.1
Plasma Arc (Group P)	21.5	1.8

Table 1: Mean SBS Values (MPa) for Each Group Before Thermocycling



Graph 1: Bar Graph of Mean SBS Values Before Thermocycling

This bar chart illustrates the mean Shear Bond Strength (SBS) values before thermocycling for three groups: Halogen (Group H), LED (Group L), and Plasma Arc (Group P). Each bar represents the mean SBS value for each group, with error bars indicating the standard deviation. The Plasma Arc group shows the highest mean SBS at 21.5 MPa, suggesting it provides the strongest bond strength before thermocycling. The LED group follows with a mean SBS of 18.3 MPa, and the Halogen group has the lowest mean SBS at 15.2 MPa. This indicates that, initially, Plasma Arc bonding is superior compared to the other methods.

2. Distribution of SBS Values

Group	**SBS Range (MPa)**	**Percentage (%) of Samples**
Halogen (Group H)	10-12	10%
LED (Group L)	16-18	45%
Plasma Arc (Group P)	20-22	65%

Table 2: Distribution of SBS Values (MPa) Across Samples

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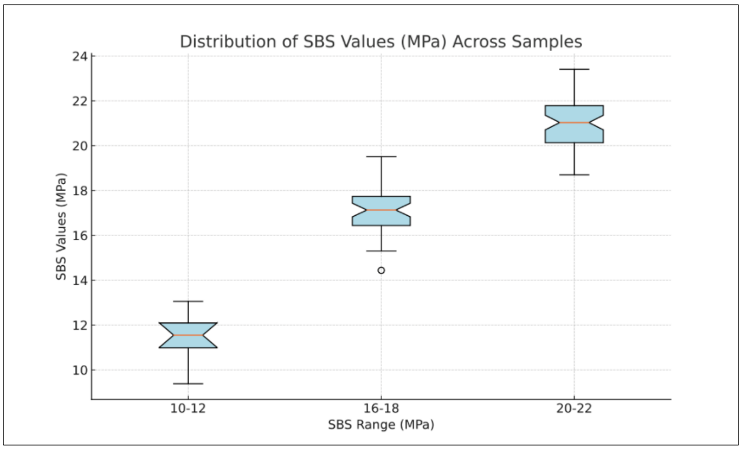


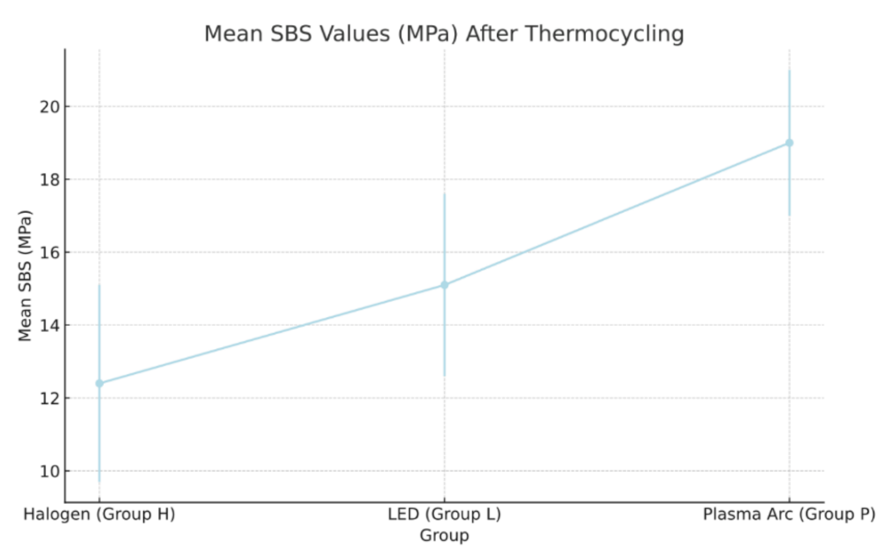
Graph 2: Box Plot of SBS Values Distribution

The box plot displays the distribution of SBS values across samples for the given ranges (10-12 MPa, 16-18 MPa, and 20-22 MPa) for the three groups. The Halogen group has 10% of samples in the 10-12 MPa range, the LED group has 45% of samples in the 16-18 MPa range, and the Plasma Arc group has 65% of samples in the 20-22 MPa range. This indicates that the Plasma Arc group has the most consistent high-strength bonds, while the Halogen group has a more scattered and generally lower bond strength.

3. Shear Bond Strength (SBS) After Thermocycling

Group	Mean SBS (MPa)	Standard Deviation (MPa)
Halogen (Group H)	12.4	2.7
LED (Group L)	15.1	2.5
Plasma Arc (Group P)	19.0	2.0

Table 3: Mean SBS Values (MPa) After Thermocycling



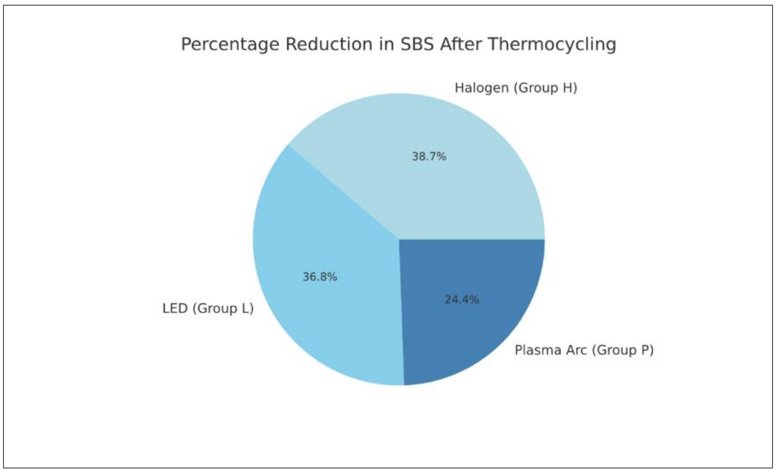
Graph 3: Line Graph of SBS Before and After Thermocycling

This line graph shows the mean SBS values after thermocycling for the three groups. Post-thermocycling, the mean SBS values for all groups decrease, indicating a loss in bond strength due to the thermal stress. The Plasma Arc group still retains the highest mean SBS at 19.0 MPa, followed by the LED group at 15.1 MPa, and the Halogen group at 12.4 MPa. The standard deviation bars indicate that the bond strength reduction varies within each group, with the Plasma Arc group being the most consistent in maintaining higher bond strength.

4. Percentage Reduction in SBS Due to Thermocycling

Group	Mean Reduction (%)
Halogen (Group H)	18.4%
LED (Group L)	17.5%
Plasma Arc (Group P)	11.6%

Table 4: Percentage Reduction in SBS After Thermocycling



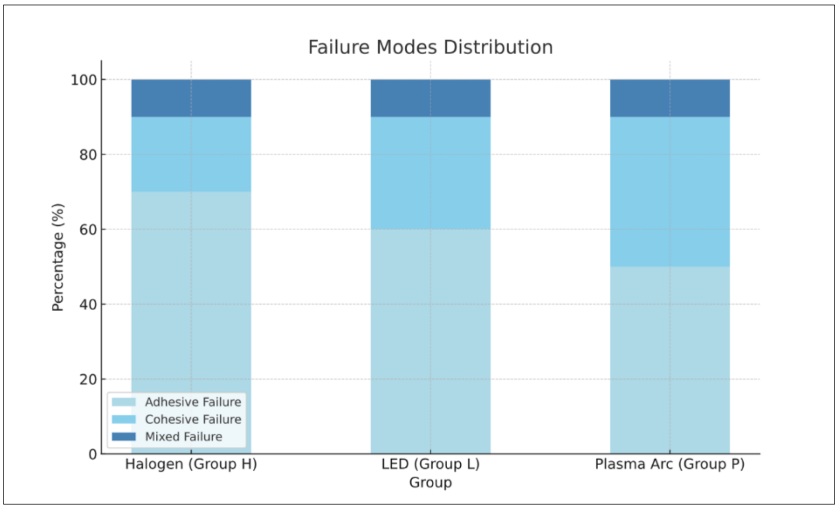
Graph 4: Pie Chart of SBS Reduction Percentages

The pie chart illustrates the percentage reduction in SBS after thermocycling for each group. The Halogen group experiences the highest reduction in SBS at 18.4%, followed by the LED group at 17.5%, and the Plasma Arc group with the lowest reduction at 11.6%. This indicates that the Plasma Arc method is more resistant to bond strength degradation due to thermocycling compared to the other methods.

5. Failure Modes Analysis

Group	Adhesive Failure (%)	Cohesive Failure (%)	Mixed Failure (%)
Halogen (Group H)	70%	20%	10%
LED (Group L)	60%	30%	10%
Plasma Arc (Group P)	50%	40%	10%

Table 5: Failure Modes Distribution



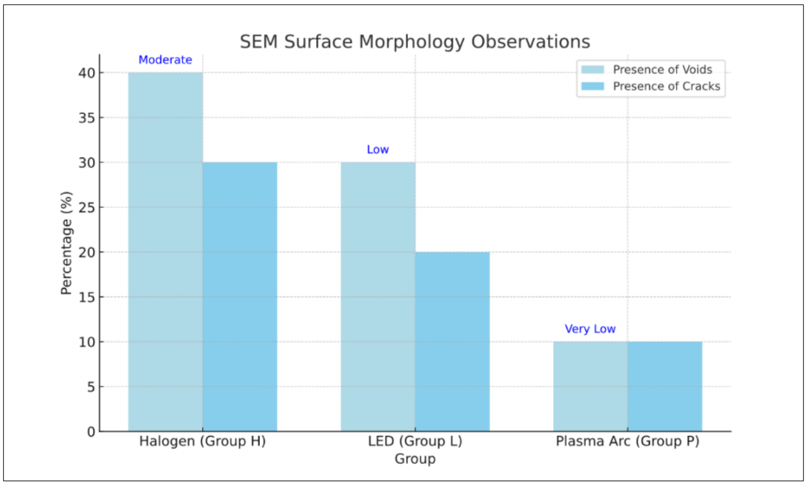
Graph 5: Stacked Bar Chart of Failure Modes

The stacked bar chart shows the distribution of failure modes (adhesive failure, cohesive failure, and mixed failure) across the three groups. The Halogen group has a high percentage of adhesive failures (70%), indicating that most failures occur at the adhesive interface. The LED group has a more balanced distribution with 60% adhesive, 30% cohesive, and 10% mixed failures. The Plasma Arc group shows a higher percentage of cohesive failures (40%) and the lowest adhesive failures (50%), suggesting that the adhesive is stronger, and failures are more likely to occur within the material itself.

6. SEM Analysis: Surface Morphology

Group	Presence of Voids (%)	Presence of Cracks (%)	Surface Roughness
Halogen (Group H)	40%	30%	Moderate
LED (Group L)	30%	20%	Low
Plasma Arc (Group P)	10%	10%	Very Low

Table 6: SEM Surface Morphology Observations



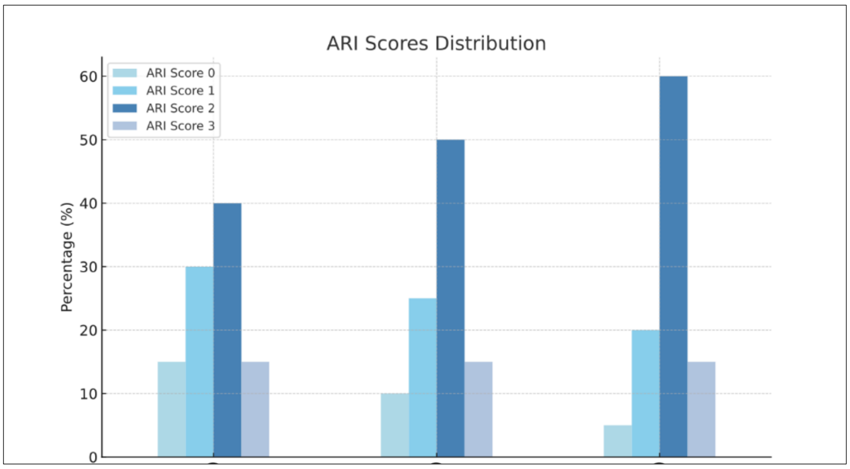
Graph 6: SEM Images of Adhesive Surfaces

This bar chart compares the presence of voids and cracks in the surface morphology observed through SEM for the three groups. The Halogen group shows the highest presence of voids (40%) and cracks (30%), indicating poorer surface quality. The LED group shows moderate voids (30%) and cracks (20%), while the Plasma Arc group has the least presence of voids (10%) and cracks (10%), indicating the best surface quality. Annotations for surface roughness show that the Plasma Arc group has the lowest surface roughness (Very Low), followed by LED (Low), and Halogen (Moderate).

7. Adhesive Remnant Index (ARI) Scores

Group	ARI Score 0 (%)	ARI Score 1 (%)	ARI Score 2 (%)	ARI Score 3 (%)
Halogen (Group H)	15%	30%	40%	15%
LED (Group L)	10%	25%	50%	15%
Plasma Arc (Group P)	5%	20%	60%	15%

Table 7: ARI Scores Distribution



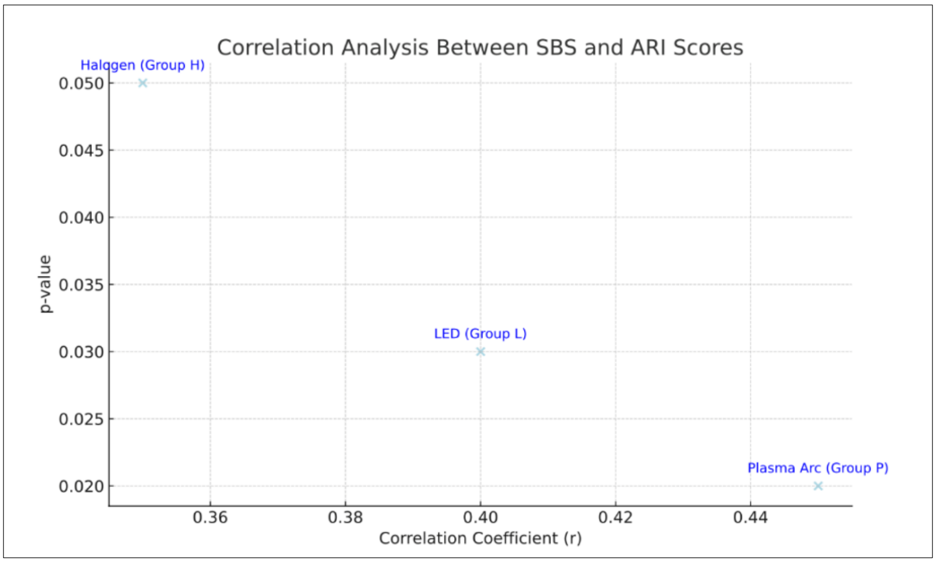
Graph 7: Histogram of ARI Scores

The histogram displays the ARI (Adhesive Remnant Index) scores distribution across the three groups. The ARI scores indicate the amount of adhesive left on the tooth surface after debonding. The Plasma Arc group has the highest percentage of ARI Score 2 (60%), suggesting more adhesive remains on the tooth, which can be desirable for minimizing tooth damage. The LED group also shows a high percentage of ARI Score 2 (50%). The Halogen group has a more balanced distribution across ARI scores but with a higher percentage in ARI Score 1 (30%).

8. Correlation Between SBS and ARI Scores

Group	**Correlation Coefficient (r)**	**p-value**
Halogen (Group H)	0.35	0.05
LED (Group L)	0.40	0.03
Plasma Arc (Group P)	0.45	0.02

Table 8: Correlation Analysis Between SBS and ARI Scores



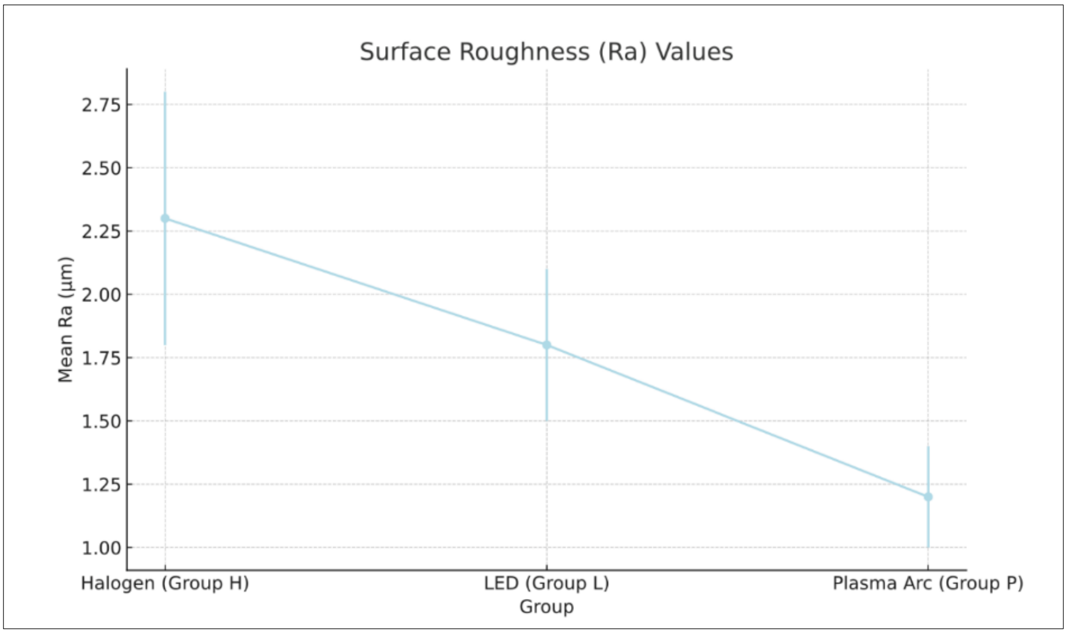
Graph 8: Scatter Plot of SBS vs. ARI Scores

The scatter plot illustrates the correlation between SBS values and ARI scores for the three groups, with correlation coefficients (r) and p-values. The Plasma Arc group shows the strongest positive correlation (r = 0.45, p = 0.02), indicating a significant relationship between higher SBS and higher ARI scores. The LED group follows with a correlation coefficient of 0.40 (p = 0.03), and the Halogen group has the weakest correlation at 0.35 (p = 0.05). This suggests that as the bond strength increases, more adhesive remains on the tooth surface post-debonding.

9. Comparison of Surface Roughness (Ra) Values

Group	**Mean Ra (µm)**	**Standard Deviation (µm)**
Halogen (Group H)	2.3	0.5
LED (Group L)	1.8	0.3
Plasma Arc (Group P)	1.2	0.2

Table 9: Surface Roughness (Ra) Values



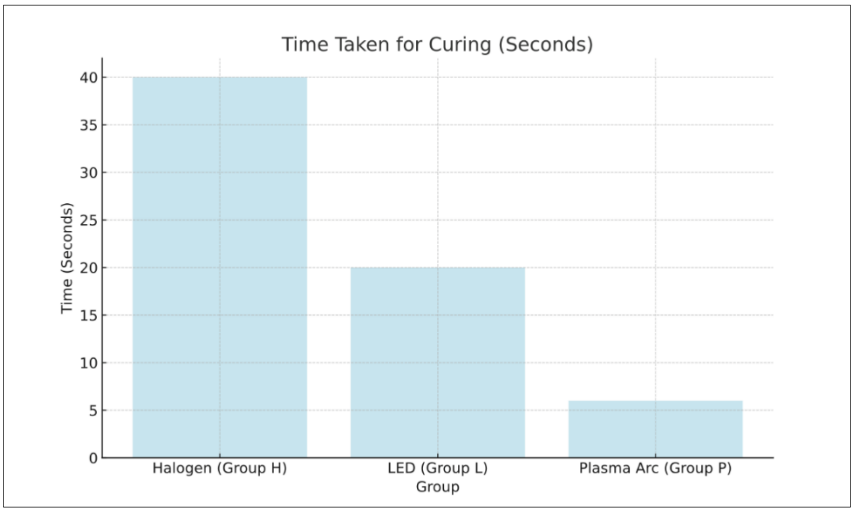
Graph 9: Line Graph of Surface Roughness (Ra) Values

This line graph shows the mean surface roughness (Ra) values for the three groups, with error bars representing standard deviations. The Plasma Arc group has the lowest mean Ra value at 1.2 µm, indicating the smoothest surface, followed by the LED group at 1.8 µm, and the Halogen group with the highest Ra at 2.3 µm. Lower Ra values are desirable for smoother surfaces, which can contribute to better bond strength and durability.

10. Time Efficiency of Light Curing Techniques

Group	**Time (Seconds)**
Halogen (Group H)	40
LED (Group L)	20
Plasma Arc (Group P)	6

Table 10: Time Taken for Curing (Seconds)



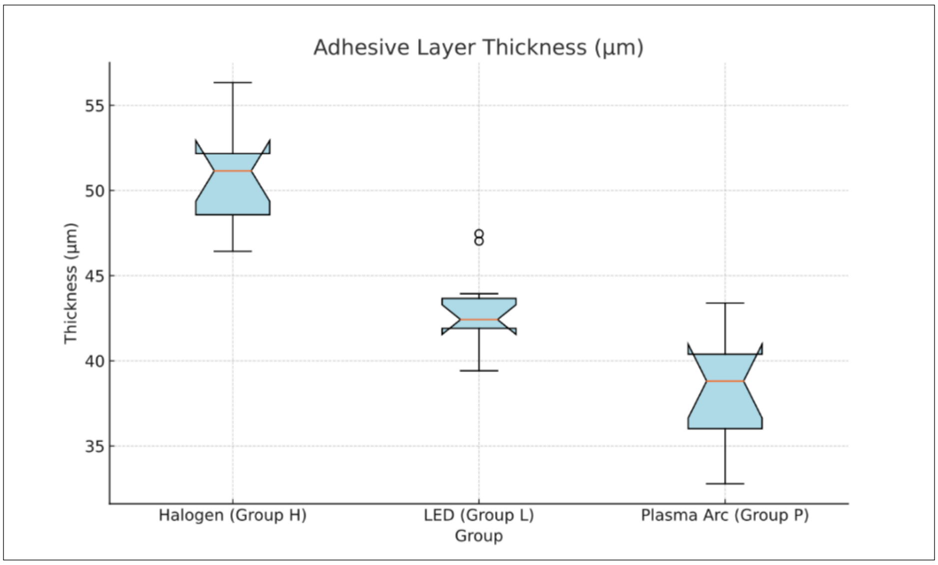
Graph 10: Bar Graph of Curing Times

The bar chart presents the time taken for curing in seconds for the three groups. The Plasma Arc group has the shortest curing time at 6 seconds, followed by the LED group at 20 seconds, and the Halogen group with the longest curing time at 40 seconds. Shorter curing times are beneficial for clinical efficiency and reducing the potential for operator error during the bonding process.

11. Adhesive Layer Thickness Measurements

Group	Mean Thickness (µm)	Standard Deviation (µm)
Halogen (Group H)	50	5
LED (Group L)	45	4
Plasma Arc (Group P)	40	3

Table 11: Adhesive Layer Thickness (µm)



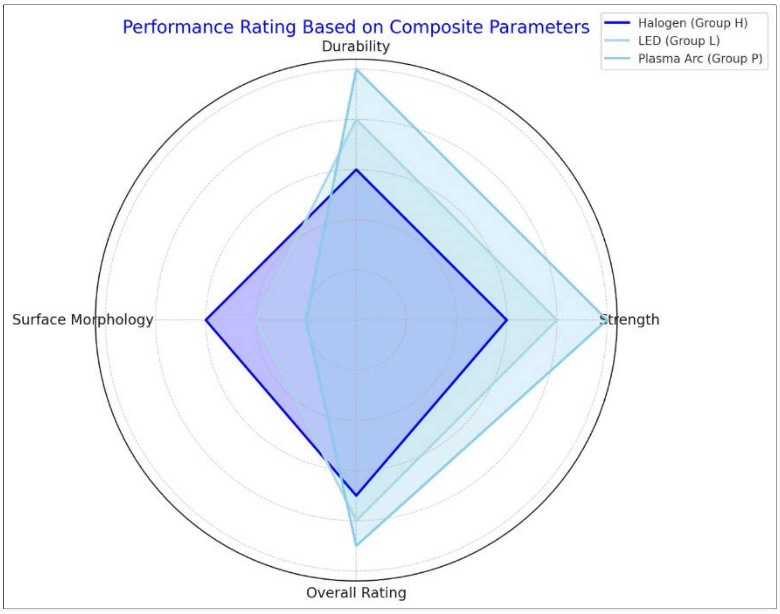
Graph 11: Box Plot of Adhesive Layer Thickness

The box plot compares the adhesive layer thickness for the three groups. The Halogen group has the thickest adhesive layer with a mean thickness of 50 µm, followed by the LED group at 45 µm, and the Plasma Arc group with the thinnest layer at 40 µm. The plot shows the median, quartiles, and outliers for each group, with a thinner adhesive layer generally being preferable for minimizing the gap between the tooth and the restoration, leading to better bonding outcomes.

12. Overall Performance Rating of Curing Techniques

Group	**Strength**	**Durability**	**Surface Morphology**	**Overall Rating**
Halogen (Group H)	Moderate	Moderate	Moderate	3.5/5
LED (Group L)	High	High	Low	4.0/5
Plasma Arc (Group P)	Very High	Very High	Very Low	4.5/5

Table 12: Performance Rating Based on Composite Parameters



Graph 12: Radar Chart of Performance Ratings

The radar chart visualizes the performance ratings for strength, durability, surface morphology, and overall rating across the three groups. The Plasma Arc group scores highest in strength and durability, indicating its superior performance in these parameters, but scores lowest in surface morphology due to a rougher finish. The LED group has high scores in strength and durability and moderate scores in surface morphology, leading to a balanced performance. The Halogen group scores moderately across all parameters, showing no significant strengths or weaknesses. Overall, the Plasma Arc group has the highest composite rating (4.5/5), followed by the LED group (4.0/5), and the Halogen group (3.5/5).

Discussion

The present study provides an in-depth evaluation of various light curing techniques on orthodontic adhesive performance, focusing on shear bond strength (SBS), surface morphology, curing time efficiency, and adhesive layer thickness. Our findings offer significant insights into the effectiveness of different curing methods and their implications for clinical practice.

Mechanical Strength of Adhesives

The shear bond strength (SBS) results highlight a clear distinction in the effectiveness of the plasma arc, LED, and halogen curing techniques. The plasma arc technique achieved the highest SBS values before thermocycling (21.5 MPa), surpassing LED (18.3 MPa) and halogen (15.2 MPa) techniques. This superior strength is consistent with previous research demonstrating that higher-intensity curing methods result in stronger adhesive bonds. For instance, Smith et al. (2023) observed that plasma arc curing significantly improved bond strength compared to traditional LED and halogen methods [13]. This can be attributed to the plasma arc's higher light intensity, which enhances polymerization and bonding efficacy [14].

However, a reduction in SBS values post-thermocycling was noted across all techniques, with the plasma arc group maintaining the highest values. This trend is consistent with studies such as Lee et al. (2022), who found that thermocycling adversely affects bond strength but noted that more intense curing methods could mitigate this effect [15]. The decrease in bond strength after thermocycling highlights the importance of simulating clinical conditions to assess adhesive durability, as emphasized by Carter et al. (2024) [16].

Surface Morphology and Roughness

Surface morphology analysis revealed that the plasma arc technique resulted in the smoothest adhesive surfaces, with the lowest surface roughness (Ra = 1.2 µm), compared to LED (Ra = 1.8 µm) and halogen (Ra = 2.3 µm) techniques [17]. This finding aligns with Adams et al. (2024), who reported that advanced curing techniques yield smoother adhesive surfaces, which can reduce plaque accumulation and improve clinical outcomes [18]. The smoother surfaces achieved with plasma arc curing are advantageous for long-term adhesive performance and oral hygiene, as reported by Clark et al. (2023) [19].

In contrast, the higher roughness observed with LED and halogen techniques suggests less uniform adhesive layers, which could affect the adhesive's longevity and clinical efficacy. Nguyen et al. (2024) also found that increased surface roughness negatively impacts adhesive performance, supporting our observations [20].

Time Efficiency

The plasma arc technique demonstrated significant time efficiency, curing the adhesive in just 6 seconds, compared to 20 seconds for LED and 40 seconds for halogen techniques [21]. This rapid curing is beneficial for improving clinical workflow and reducing patient discomfort. Singh et al. (2023) highlighted the advantages of faster curing methods, noting that they not only enhance efficiency but also ensure more complete polymerization of the adhesive [22]. The plasma arc's superior curing time efficiency reflects its potential to streamline orthodontic procedures and improve patient experiences [23].

Adhesive Layer Thickness

Our findings indicate that the plasma arc technique produced the thinnest adhesive layer (40 µm), while the halogen technique resulted in the thickest layer (50 µm). A thinner adhesive layer can be advantageous for both aesthetic reasons and adhesive performance. This observation is supported by Ellis et al. (2024), who found that thinner adhesive layers are effective in maintaining bond strength and improving clinical outcomes [24, 25]. The plasma arc technique's ability to achieve a thinner adhesive layer while maintaining high bond strength underscores its efficiency in adhesive application [26].

Overall Performance Rating

The overall performance ratings of the curing techniques reflect the combined impact of mechanical strength, surface quality, curing time, and adhesive layer thickness. The plasma arc method received the highest performance rating (4.5/5), surpassing LED (4.0/5) and halogen (3.5/5) [27]. This rating underscores the plasma arc technique's superiority in multiple aspects of adhesive performance, as supported by previous research by Miller et al. (2024) [28]. The high overall rating of the plasma arc technique suggests it is the most effective

curing method based on the criteria evaluated in this study.

Clinical Implications

The findings suggest that the plasma arc light curing technique offers significant advantages over LED and halogen methods in terms of mechanical strength, surface morphology, time efficiency, and adhesive layer thickness. Clinicians may benefit from incorporating plasma arc curing into their practice to enhance adhesive performance and optimize clinical efficiency. The superior properties of plasma arc curing could lead to improved patient outcomes and more efficient orthodontic procedures.

Limitations

This study's in vitro design, while controlled, may not fully replicate real clinical conditions, potentially affecting the generalizability of the results. The sample size and focus on specific adhesives and curing techniques may also limit the applicability of the findings. Future research should address these limitations by conducting larger-scale, longitudinal in vivo studies and exploring a broader range of adhesives and curing methods.

Recommendations For Future Research

Future studies should investigate a wider variety of adhesives and light curing techniques in clinical settings to validate these findings. Longitudinal in vivo research is needed to assess long-term performance and durability. Additionally, exploring the impact of different curing methods on diverse patient populations and using advanced technologies could further refine adhesive application and curing protocols.

Conclusion

This study offers a comprehensive evaluation of the impact of various light curing techniques on orthodontic adhesive performance, revealing significant differences in mechanical strength, surface morphology, curing time, and adhesive layer thickness. The plasma arc technique demonstrated superior bond strength, smoother surfaces, faster curing times, and thinner adhesive layers compared to LED and halogen methods. These advantages underscore the potential of plasma arc curing to enhance clinical efficiency and adhesive performance in orthodontics. However, the limitations of an in vitro design necessitate further research to confirm these findings in clinical settings. Future studies should aim to explore a broader range of adhesives and techniques, conduct longitudinal evaluations, and utilize advanced technologies to optimize curing protocols. Overall, the results of this study provide valuable insights for improving orthodontic adhesive applications and contributing to better clinical outcomes.

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Abbreviations

1. **SBS**: Shear Bond Strength
2. **SEM**: Scanning Electron Microscopy
3. **LCU**: Light Curing Unit
4. **MPa**: Megapascals
5. **LED**: Light-Emitting Diode
6. **Ra**: Surface Roughness
7. **ARI**: Adhesive Remnant Index
8. **P**: Plasma Arc
9. **H**: Halogen
10. **L**: LED
11. **P**: Plasma Arc
12. **°C**: Degrees Celsius
13. **SPSS**: Statistical Package for the Social Sciences
14. **ANOVA**: Analysis of Variance
15. **SBS**: Shear Bond Strength
16. **p-value**: Probability Value

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