Optimizing Polymerization of Dental Resins: Mechanical Strength and Thermal Impacts of Diode Lasers at 405nm and 450nm

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Abstract
Background: The aesthetic and mechanical properties of resin-based dental composites make them a popular choice for restorative dentistry. The longevity and efficacy of these materials are significantly influenced by the polymerization process. Elevated temperatures during the polymerization process can compromise the integrity of the tooth pulp and adjacent tissues. The enhancement of surface hardness and compressive strength signifies an elevation in the quality and longevity of aesthetic restorations achieved through laser application. The mechanical properties and thermal effects of dental composite polymers are examined in this study in relation to blue diode laser polymerization (405nm and 450nm). **Methods and materials**: Thirty cylindrical specimens of Tetric N-Ceram composite resin were categorized into three groups: conventional curing (Gc), 405nm diode laser curing (G1), and 450nm diode laser curing (G2). Surface microhardness (VHN), compressive strength (MPa), and temperature rise during polymerization were statistically analyzed and measured. **Results**: The G1 group (405nm diode laser) achieved the highest surface hardness (55.21 VHN) and the lowest temperature rise (5.9°C), while also attaining a comparable compressive strength (216.09 MPa). The G2 group (450nm diode laser) demonstrated the highest surface hardness (56.15 VHN) but also caused the most substantial temperature increase (9.4°C), which could pose a risk to pulp tissues. Conventional curing (Gc) yielded moderate results, including a temperature increase of 7.1°C and a decrease in surface hardness (48.20 VHN). **Conclusion**: The 405nm diode laser is a viable alternative to conventional curing methods due to its clinically favorable balance of minimal thermal effects and enhanced mechanical properties. The 450nm diode laser, in contrast, may increase thermal risks despite attaining superior surface hardness. Future research should concentrate on the optimization of laser parameters to optimize mechanical efficacy and safety in clinical applications. **Keywords**: Blue diode laser; light cure; polymerization efficiency; surface microhardness; compressive strength.

Introduction

Fiber reinforced resins have greatly contributed and helped towards the development of modern restorative concepts and outcomes pertaining to aesthetics, durability as well as flexibility. The field of restorative dentistry has witnessed a notable increase in the development of materials with excellent esthetic qualities(Mohammed NA et al.;2024) The rising desire for tooth-colored restorations, cosmetic dental operations, and the conservation of tooth structure, along with significant advancements in adhesive technology, has resulted in the extensive application of direct composite restorations.

restoration. Thus, the efficiency of their polymerization process is critical because, interfering with the mechanical properties, wear and clinical performance of restorations. Yaroub, M et al (2014). However, too little polymerization may lead to less favourable mechanical properties, greater polymerization shrinkage and marginal disintegration and all these could give toughness shape to the failure of the restoration process (Sakaguchi et al., 2022). For this reason, optimising the polymerization process is very crucial, in order to get restorations that are excellent in quality and functional durability The light-curing unit plays a more influential role in the basic properties of resin based composites. Quartz-tungsten-halogen (QTH) units have been widely used for polymerizing resin -based dental materials for decades. QTH units exhibit several shortcomings, so, as an alternative, light -emitting diode (LED) light curing units were introduced for polymerizing resin -based composites. However, conflicting results have often been observed in the literature as related to the effects of both light curing units. Recently, resin-based composite curing lights have been developed that have higher intensities and shorter curing cycles which help speed the resin-based curing shalan LA et al(2017). Due to advanced developments blue diode lasers operating within the 405-450 nm wave length have been used. These lasers present a modern technique for the polymerization of composite resins. Before, the LCUs which are halogen and plasma arc systems are used in order to initiate polymerization (Meereis et al., 2023). These systems have the following disadvantages, for instance, the irregular source of energy and heat build-up. Blue diode lasers on the other hand give a wavelength that is relatively narrow and which closely matches that of camphorquinone, the most common photoinitiator in most dental composites (Jung et al., 2024). This makes it possible to provide the right energy distribution that can enhance conversion degree and reduce the number of time taken for curing the resin besides enhancing mechanical characteristics of the resin. That is why the increase in temperature during laser polymerization is a serious concern, even though such possible advantages are available. This raises the temperature of the tooth pulp and the tissues that are around it and the extreme heat can cause thermal damage to the pulp which in return becomes fatal for the successful restoration (Lee et al., 2023).The objective of this study is to assess the mechanical properties and the temperature increase associated with the polymerization of composite resins. This study attempts to investigate if blue diode lasers offer a greater balance between increased mechanical performance and decreased thermal risk by comparing these outcomes to those achieved from conventional curing techniques for purpose of improving the lifetime of restorations and the safety of patients.

2.materal and method.

Study Design and Sample Preparation This experimental study employed 30 composite resin specimens that were manufactured using a standardized Teflon mold with dimensions of 6 mm in diameter and 4 mm in height. Tetric N-Ceram
(Ivoclar Vivadent, Germany) was the composite material employed. In order to guarantee uniformity, the material was gradually introduced into the mold and condensed between two glass slides. Each specimen was examined under a magnifying glass for surface defects, fractured edges, warpage, or porosities, and all

defective samples were excluded. The accepted specimens were subjected to ultrasonic cleaning for a duration of 10 minutes to eliminate debris. Subsequently, they were stored in distilled water at 37°C for 48 hours to replicate oral conditions.

Study Groups

The specimens were randomly assigned to three groups, with a total of 10 specimens in each group.

Control Group (Gc): Polymerized for 20 seconds using a conventional light-curing unit (LED).

Group 1 (G1): Polymerized for 20 seconds using a blue diode laser (405 nm, 0.7 W/cm²).

Group 2 (G2): Polymerized for 20 seconds using a blue diode laser (450 nm, 0.7 W/cm²).

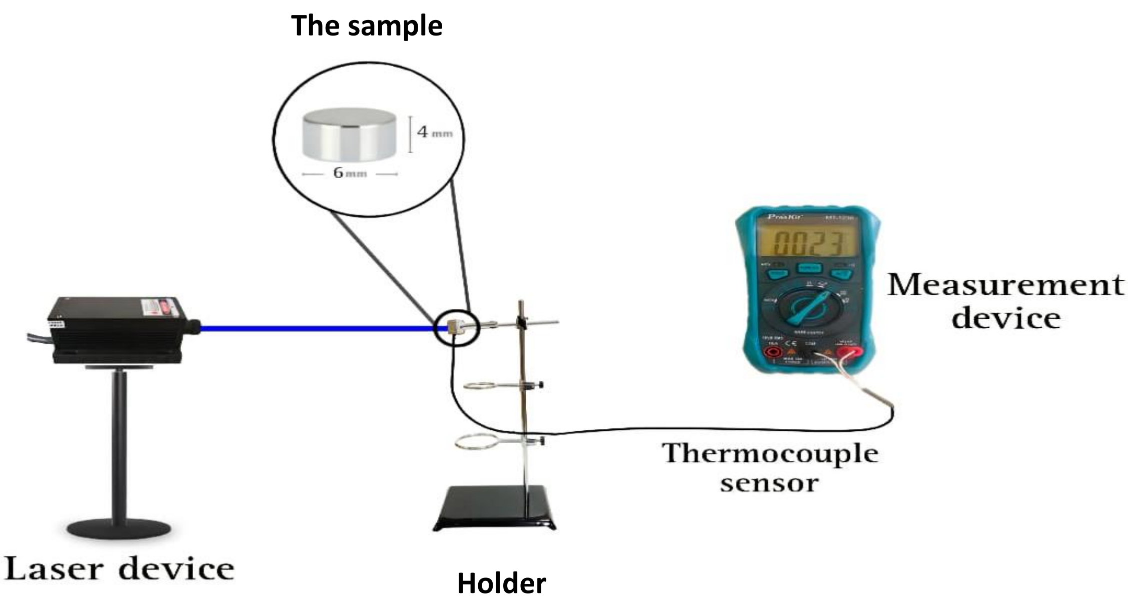

Fig.1 Experimental Setup.

2.2 procedure

2.2.1 Measurement of tempreture rise during polymerization

Digital thermocouple (Proskit, MT1236, Taiwan) was used to measure the tempreture during polymerization process the sensor put under the sample Fig.1 .

2.2.2 Microhardness assessment

A micro hardness tester was employed to ascertain Vickers micro hardness, utilizing a diamond indenter with a square base and a high-resolution optical microscope with 400x magnification. A load of 1000 g (9.8 N) was applied for a duration of 15 seconds. The microhardness of the surfaces was assessed utilizing a Vickers hardness tester. (MVK-H1, Akashi, Tokyo, Japan).

2.2.3 compressive strength test

Compression tests were conducted with a universal testing equipment (XWW-50KN, China) at a crosshead velocity of 1 mm/min. The compressive strength (CS) (σc in megapascals) was determined using the subsequent formula: σc = P/A, where P represents the maximum failure load (in newtons) and A is the cross-sectional area of the specimen.

3. Statistical analysis

All data were analyzed using the Statistical Package for Social Sciences (SPSS, version 26.0, IBM Corp., Armonk, NY, USA). The Shapiro-Wilk test was employed to assess data normality. One-way analysis of variance (ANOVA) was used to determine intergroup differences, followed by post-hoc pairwise comparisons (Dunnett's T3 for temperature rise and Tukey HSD for hardness). A p-value of <0.05 was considered statistically significant.

4.Result

Temperature Rise During Polymerization

The temperature rise differed significantly among the three groups (F=24.85F = 24.85F=24.85, p<0.001p < 0.001p<0.001; Table 2). Group 2 (450 nm diode laser) demonstrated the highest mean temperature increase (9.4±1.71∘C9.4 \pm 1.71^\circ C9.4±1.71∘C), followed by the Control Group (7.1±0.45∘C7.1 \pm 0.45^\circ C7.1±0.45∘C) and Group 1 (405 nm diode laser; 5.9±0.76∘C5.9 \pm 0.76^\circ C5.9±0.76∘C). Post-hoc analysis (Dunnett's T3; Table 3) revealed significant differences between all groups:

G1 vs. G2 (p<0.001p < 0.001p<0.001)

G1 vs. Gc (p=0.003p = 0.003p=0.003)

G2 vs. Gc (p=0.006p = 0.006p=0.006).

As illustrated in Figure 5, Group 2 exhibited a markedly higher temperature increase, raising concerns about thermal safety during polymerization, particularly in clinical settings where pulp tissue may be affected.

Table 1. Normality test of studied variables

Vars.		Gc	G1	G2
Δ°C	Statistic	0.88	0.86	0.94
	P value	0.14	0.08	0.59
Hardness	Statistic	0.93	0.92	0.91
	P value	0.50	0.37	0.32
Compressive	Statistic	0.86	0.92	0.97
	P value	0.07	0.41	0.93

Table 2. Descriptive and statistical test of change in temperature (Δ°C) among study groups

Groups	N	Mean	±SD	±SE	Minimum	Maximum	F	P value
Gc	10	7.10	0.45	0.14	6.50	8.00	24.85	**0.000**
G1	10	5.95	0.76	0.24	5.00	7.00		
G2	10	9.40	1.71	0.54	7.00	12.00		

Table 3. Multiple pairwise comparison of change in temperature (Δ°C) among study groups using Dunnett's T3

Groups		Mean difference	p value
Gc	G1	1.15	**0.003**
	G2	-2.30	**0.006**
G1	G2	-3.45	**0.000**

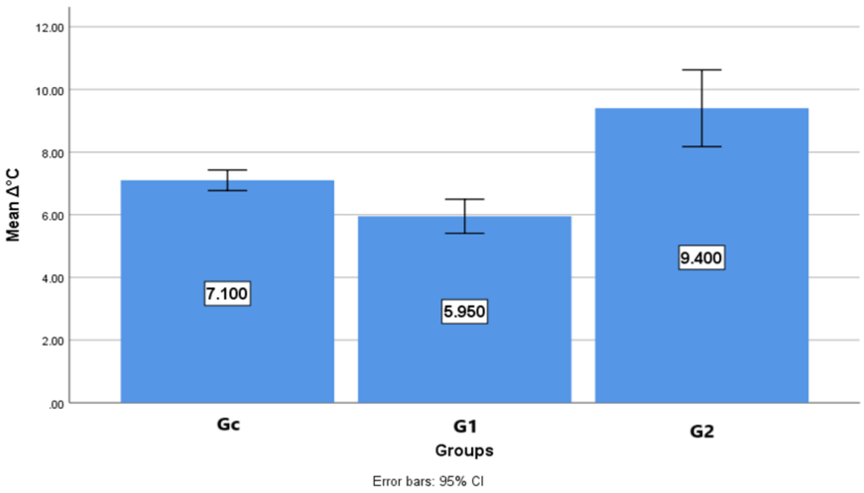

Fig. 5. : change in temperature (Δ°C) among study groups.

Surface Microhardness

Surface hardness measurements (VHN) were significantly affected by the polymerization method (F=12.27F = 12.27F=12.27, p<0.001p < 0.001p<0.001; Table 4). The highest mean hardness was observed in Group 2 (56.15±4.6056.15 \pm 4.6056.15±4.60 VHN), followed by Group 1 (55.21±3.2655.21 \pm 3.2655.21±3.26 VHN), with the Control Group showing the lowest values (48.20±3.7848.20 \pm 3.7848.20±3.78 VHN). Post-hoc Tukey analysis (Table 5) indicated significant differences:
Gc vs. G1 (p=0.001p = 0.001p=0.001)
Gc vs. G2 (p=0.002p = 0.002p=0.002)
No significant difference between G1 and G2 (p=0.934p = 0.934p=0.934).
Figure 6 highlights these differences, demonstrating that both laser groups outperformed the Control Group in hardness, suggesting enhanced mechanical properties due to diode laser polymerization.

Table 4. Descriptive and statistical test of surface hardness among study groups.

Groups	N	Mean	±SD	±SE	Minimum	Maximum	F	P value
Gc	10	48.20	3.78	1.19	40.20	53.00	12.27	**0.000**
G1	10	55.21	3.26	1.03	51.45	61.15		
G2	10	56.15	4.60	1.45	50.10	62.89		

Table 5. Multiple pairwise comparison of surface hardness among study groups using

Tukey HSD

Groups		Mean difference	p value
Gc	G1	-7.01	**0.001**
	G2	-7.95	**0.002**
G1	G2	-0.93	0.934

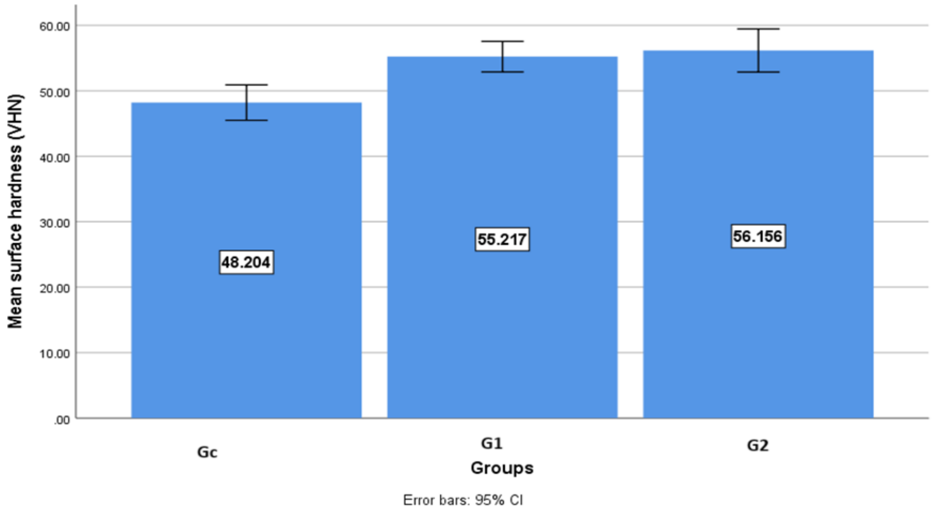

Fig. 6. : Surface hardness (VHN) among study groups.

Compressive strength:

Compressive strength was highest in Group 1 (216.09±41.98216.09 \pm 41.98216.09±41.98 MPa), followed by the Control Group (214.03±50.47214.03 \pm 50.47214.03±50.47 MPa), and lowest in Group 2 (177.77±39.19177.77 \pm 39.19177.77±39.19 MPa; Table 6). However, ANOVA did not detect significant differences among groups (F=2.38F = 2.38F=2.38, p=0.11p = 0.11p=0.11).
Although Group 1 displayed marginally higher compressive strength than the Control Group, Figure 7 shows substantial overlap in the data, reflecting the absence of statistically significant differences. This suggests that diode laser polymerization, particularly at 405 nm, may achieve similar compressive strength levels compared to conventional methods.

Table 6. Descriptive and statistical test of compressive strength among study groups.

Groups	N	Mean	±SD	±SE	Minimum	Maximum	F	P value
Gc	10	214.03	50.47	15.96	157.40	301.49	2.38	**0.11**
G1	10	216.09	41.98	13.27	160.00	299.00		
G2	10	177.77	39.19	12.39	118.00	249.00		

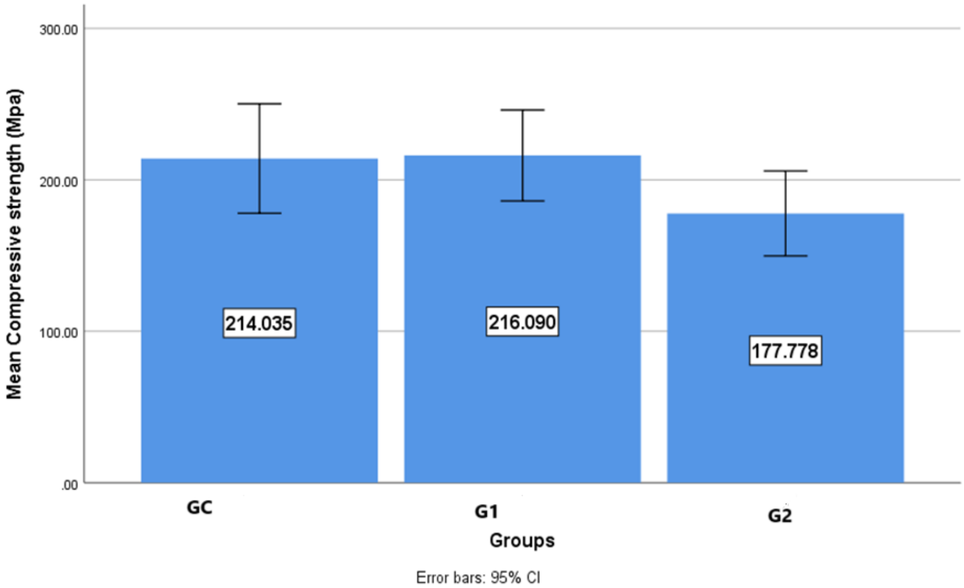

Fig. 7. : Compressive strength (Mpa) among study groups.

5.Discussion

Temperature Rise and Pulp Safety

The study revealed a significant temperature rise during polymerization, with Group 2 (450 nm diode laser) showing the highest increase (9.4±1.71∘C9.4 \pm 1.71^\circ C9.4±1.71∘C). This level of heat generation exceeds the threshold for potential pulp damage, which has been reported to occur with increases above 5.5∘C5.5^\circ C5.5∘C (Lee et al., 2023). While the 405 nm diode laser (Group 1) showed the lowest temperature rise (5.9±0.76∘C5.9 \pm 0.76^\circ C5.9±0.76∘C), it approached this critical threshold, suggesting the need for careful calibration of laser parameters to prevent adverse thermal effects.

This result aligns with prior studies indicating that diode lasers produce concentrated energy, leading to localized heat generation (Rakić et al., 2024). However, the monochromatic and coherent properties of diode lasers allow for more efficient energy absorption by photoinitiators like camphorquinone, potentially reducing the exposure time needed and mitigating thermal risks when used appropriately.

Surface Microhardness and Mechanical Properties

Both diode laser groups demonstrated significantly higher surface hardness compared to the Control Group (p < 0.01). Group 2 exhibited the highest mean hardness (56.15±4.6056.15 \pm 4.6056.15±4.60 VHN), followed closely by Group 1 (55.21±3.2655.21 \pm 3.2655.21±3.26 VHN). This improvement in hardness can be attributed to the laser's ability to achieve a higher degree of conversion in the resin matrix, enhancing the cross-linking density (Maucoski et al., 2023).
Enhanced surface hardness is clinically significant, as it improves the wear resistance, color stability, and overall durability of composite restorations (Michailidou et al., 2023). The lack of a significant difference between the two diode laser groups suggests that both wavelengths (405 nm and 450 nm) are effective in improving mechanical properties. However, given the thermal concerns with the 450 nm laser, the 405 nm diode laser may be the safer choice.

Compressive Strength and Clinical Relevance

While compressive strength was highest in Group 1 (216.09±41.98216.09 \pm 41.98216.09±41.98 MPa), followed by the Control Group (214.03±50.47214.03 \pm 50.47214.03±50.47 MPa), the differences were not statistically significant (p=0.11p = 0.11p=0.11). This finding suggests that diode laser polymerization at 405 nm can achieve comparable mechanical strength to conventional LED curing, supporting its use in clinical applications.
The slightly lower compressive strength in Group 2 (177.77±39.19177.77 \pm 39.19177.77±39.19 MPa) could be due to increased temperature during polymerization, which may negatively affect the material's structural integrity (Thanoon et al., 2024). The specimens examined in this study often possess elevated filler content due to the use of nanofillers. Nanoparticles embedded in polymer matrix have attracted increasing interest because of the unique mechanical, optical, electrical and magnetic properties displayed by nanocomposites at low nano-filler concentrations. This importance is due to the effect of the unique nature of the nanosized filler on the bulk properties of polymer-based nanocomposites (Al-Ameery et al.,2013).The included nanoparticles will diminish interparticle spacing, reduce strain localization, and enhance fatigue resistance. This highlights the importance of optimizing laser settings to balance mechanical outcomes with thermal safety.

Comparison with Literature

These findings are consistent with previous research emphasizing the advantages of diode lasers in enhancing polymerization efficiency and mechanical properties (Jung et al., 2024; Rakić et al., 2024). However, the observed temperature increases in Group 2 align with studies warning about thermal risks associated with higher energy outputs (Maucoski et al., 2023).
In contrast, the lack of significant improvement in compressive strength differs from reports suggesting that diode lasers outperform LEDs in this metric (Sakaguchi et al., 2022). This discrepancy may stem from variations in composite composition, laser parameters, or experimental design, underscoring the need for standardized protocols.

Clinical implication:

The research endorses the application of diode lasers, namely at 405 nm, as a feasible substitute for traditional LED curing in composite resins. The enhanced surface hardness signifies superior resistance to occlusal pressures and increased durability of restorations. Nonetheless, the risk of heat injury, especially with the 450 nm diode laser, requires careful application and additional research. Clinicians ought to utilize diode lasers in scenarios necessitating improved mechanical characteristics, while assuring sufficient cooling or reduced exposure durations to safeguard pulp tissues.

Limitations and Future Directions

Sample Size: While sufficient for initial analysis, a larger sample size is needed to confirm findings and enhance statistical power.
Thermal Management: Future studies should investigate methods to mitigate heat generation during laser polymerization, such as intermittent curing or external cooling.
Long-term Performance: Assessing wear resistance, marginal integrity, and color stability under simulated oral conditions will provide insights into the long-term clinical efficacy of diode lasers.
Optimization of Laser Settings: Research is needed to identify the ideal wavelength, power density, and exposure time for balancing mechanical performance with thermal safety.

7. Conclusions

Diode lasers, especially at 405 nm, provide substantial benefits in enhancing the mechanical properties of composite resins while reducing heat concerns relative to 450 nm lasers. These findings underscore the efficacy of diode lasers as a secure and effective polymerization technique, contingent upon the optimization of their parameters. Additional study is required to enhance these strategies and investigate their application in other therapeutic contexts.

References

1. Sakaguchi, R.L., et al. (2022). Polymerization shrinkage stress of composites photoactivated by different light sources. Journal of Dental Research. PubMed.
2. Meereis, C.T., et al. (2023). Effect of a Diode Laser (445 nm) on Polymerization Efficiency of a Preheated Resin Composite Used for Luting of Indirect Composite Restorations. Operative Dentistry. Allen Press.
3. Jung, J.H., et al. (2024). Blue Laser for Polymerization of Bulk-Fill Composites: Influence on Polymerization Kinetics. Materials. MDPI.
4. Lee, J.H., et al. (2023). Temperature Rise During Laser Polymerization: Implications for Clinical Safety. Dental Materials. PMC.
5. Rakić, M., Ivanišević, A., Baraba, A., Agović, S. Č., Šošić, A., & Klarić, E. (2024). Blue Laser for Polymerization of Bulk Fill Composites: Influence on dentin bond strength and temperature rise during curing and co-curing method. *Lasers in medical science*, *39*(1), 93.
6. Maucoski, C., Price, R. B., & Arrais, C. A. G. (2023). Temperature changes and hardness of resin-based composites light-cured with laser diode or light-emitting diode curing lights. *Odontology*, *111*(2), 387-400.
7. Thanoon, H., Price, R. B., & Watts, D. C. (2024). Thermography and conversion of fast-cure composite photocured with quad-wave and laser curing lights compared to a conventional curing light. *Dental Materials*, *40*(3), 546-556.
8. Michailidou, S., Dionysopoulos, D., Papadopoulos, C., Naka, O., Andriotis, E., Fatouros, D., & Tolidis, K. (2023). Effect of a diode laser (445 nm) on polymerization efficiency of a preheated resin composite used for luting of indirect composite restorations. *Operative Dentistry*, *48*(5), 513-523.
9. Maucoski, C., Price, R. B., Sullivan, B., Guarneri, J. A. G., Gusso, B., & Arrais, C. A. G. (2023). In-vitro pulpal temperature increases when photo-curing bulk-fill resin-based composites using laser or light-emitting diode light curing units. *Journal of Esthetic and Restorative Dentistry*, *35*(4), 705-716.
10. Price, J. M., Prabhakaran, A., & West, C. M. (2023). Predicting tumour radiosensitivity to deliver precision radiotherapy. *Nature Reviews Clinical Oncology*, *20*(2), 83-98.
11. Yaroub, M. and Hameed, M. R. 2014. Evaluation of marginal gap at the composite/enamel interface in Class II composite resin restoration by SEM after thermal and mechanical load cycling (An in vitro comparative study). Journal of Baghdad College of Dentistry. 26, 4 (Dec. 2014), 63–70.
12. Shalan LA, Thiab SH. The Effect of Different Light Cure Systems on Microhardness of Bulk Fill Composite Materials. J Bagh Coll Dent [Internet]. 2017 Jun. 15

13.Al-Ameery, Aysser & Bawi, Zainab & Hanna, Waleed. (2013). Study of the Effect of Alumina Nano Particles Addition on Some Mechanical and Physical Properties of an Epoxy Resin Polymer Matrix Composite. Journal of King Abdulaziz University-Engineering Sciences. 24. 23-44. 10.4197/Eng.24-1.2.

14.Mohammed NA, Mahdi ZF, Abdulhameed BS. The effect of pulsed Er,Cr:YSGG laser scanning on the adhesion strength of lithium disilicate to tooth dentin.Journal of Emergency Medicine, Trauma & Acute Care. 2024(1):10 https://doi.org/10.5339/ jemtac.2024.cism.10