ORIGINAL ARTICLE

Comparative Histological Analysis of Novel Bioceramic Materials with Adjunctive Diode Laser Therapy in Vital Pulp Therapy: An Experimental Study

Aim: *This study aimed to histologically evaluate dentin bridge formation and pulpal response following direct pulp capping using either mineral trioxide aggregate (MTA) or Well-Root PT, with and without adjunctive diode laser (DL) application, and to assess the independent effects of DL on pulpal tissues.*
Methodology: *Ninety-six teeth from eight healthy adult mongrel dogs underwent Class V cavity preparation with mechanical pulp exposure. Specimens were randomly assigned to three primary groups: Group I (control) with Teflon disc placement; Group II with MTA; and Group III with Well-Root PT. Each group was further subdivided based on the application or absence of an 810 nm DL pretreatment. Histological samples were collected at 2- and 8-weeks post-treatment to assess pulpal response and dentin bridge formation.*
Results: *Chi-square analysis showed statistically significant differences ($P < 0.05$) between the control group and both MTA and Well-Root PT groups at both time points. No significant differences ($P > 0.05$) were observed between the MTA and Well-Root PT groups, regardless of laser application. Similarly, DL pretreatment did not produce significant differences in histological outcomes within any group.*
Conclusion: *From a clinical perspective, Well-Root PT represents a viable alternative to MTA for direct pulp capping. However, the application of an 810 nm diode laser did not significantly enhance regenerative outcomes for either bioceramic materials.*

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Introduction

The dental pulp is a highly specialized connective tissue composed of nerve fibers, blood vessels, and immune cells, playing a vital role in maintaining pulpal homeostasis and exhibiting a remarkable regenerative capacity in response to external insults (1). This dynamic tissue serves as the vital core of the tooth, responsible for dentin formation, sensory function, and initiating defensive responses to pathological challenges (2).

Vital pulp therapy aims to preserve dental pulp health in cases of deep caries or trauma through pulp capping and pulpotomy techniques (3). It is commonly used in primary and immature permanent teeth and has more recently been applied to symptomatic mature permanent teeth to maintain vitality and potentially avoid root canal treatment, with the primary goal of preserving pulp vitality long term and preventing the need for non-surgical root canal therapy (3, 4). The success of vital pulp therapy depends on the protective material, as well as factors such as how long the pulp is exposed to the mouth, microbial level, root development stage, extent of pulp removal, and the restoration method used (5). Direct pulp capping represents a conservative vital pulp therapy that involves placing biocompatible materials directly onto exposed pulp tissue to prevent bacterial microleakage, stimulate reparative dentinogenesis, and maintain pulp vitality (6, 7). The quality of resulting reparative dentin, including its quantity, structural homogeneity, and presence of organized dentinal tubules, serves as a critical determinant for treatment success (8, 9).

The introduction of bioceramic materials has significantly enhanced the prognosis of direct pulp capping, with mineral trioxide aggregate (MTA) demonstrating high success rates of in clinical studies (10, 11). MTA exhibits superior biocompatibility, excellent sealing properties, and antimicrobial activity (12). However, conventional MTA presents challenges including prolonged setting time, difficult handling characteristics, and technique-sensitive mixing procedures (13, 14).

Recent advances have led to premixed formulations such as Well-Root PT (15). Well-Root PT is a ready-to-use bioceramic paste for root canal repair and pulp capping. It is composed mainly of calcium aluminosilicate, which forms the structural basis of the material and provides its bioactive properties, with zirconium oxide as a radiopacifier (16). The formulation also includes fillers and thickeners to improve consistency and handling. The material sets in the presence of moisture, ensuring chemical stability, and a durable, shrinkage-free seal (17). Moreover, Well-Root PT offer optimal biocompatibility, superior ease of application, reduced setting time, and potent antibacterial effects (18, 19). These next-generation bioceramics demonstrate comparable biological responses to conventional MTA while addressing practical limitations (20, 21).

Diode laser therapy (DL) has emerged as a promising adjunctive treatment that stimulates biological processes at the cellular level (22, 23). The 810 nm wavelength offers an optimal balance for dental applications, providing deep tissue penetration while minimizing thermal side effects, making it well-suited for procedures such as DL therapy (24). Previous studies have demonstrated that 810 nm diode laser irradiation can enhance pulpal healing responses and stimulate reparative dentin formation (25, 26).

Despite growing evidence supporting the individual efficacy of advanced bioceramic materials and DL therapy, limited research has explored their potential synergistic effects in direct pulp capping procedures. To our knowledge, no previous studies have evaluated the histomorphological effects of combining DL with Well-Root PT for this application. Therefore, this study was designed to assess pulpal response and reparative dentinogenesis following direct pulp capping using Well-Root PT compared to MTA, both with and without adjunctive 810 nm DL pretreatment, through histomorpho-

logical analysis in a mongrel dog model.

Material and Methods

Study design

The study was conducted at the Department of Surgery, Anesthesiology, and Radiology, Faculty of Veterinary Medicine, Suez Canal University, Egypt. Ethical approval was obtained from the Research Ethics Committee (REC) of the Faculty of Dentistry, Suez Canal University (Approval No. 529/2022). The study adhered to established ethical standards and animal research regulations and complied with the ARRIVE guidelines.
The study was designed as a randomized, controlled experimental trial. To determine the minimum number of dogs needed, a sample size calculation was performed using G*Power version 3.1.9.2 (27), based on data from previous research (28, 29). According to the sample size calculation, eight mature male mongrel dogs with intact dentition were included in this study. The dogs were between 12 and 24 months old and weighed between 14 and 17 kg. Prior to the start of the study, they were housed in the animal facility for a two-week acclimatization period, during which they were closely monitored for any signs of health issues through repeated physical examinations, including evaluation of the oral cavity and teeth. The dogs were fed a standard diet that met the nutritional requirements established by the National Research Council and were provided with unrestricted access to water. The incisor teeth of the eight dogs (n = 96) were randomly assigned to three groups (32 incisor teeth each) based on the pulp capping material used. Group I served as the control group and received Teflon discs only, while Group II underwent pulp capping with MTA, and Group III with Well-Root PT. Each group was further divided into two subgroups based on DL application: subgroups IA, IIA, and IIIA (without DL) and subgroups IB, IIB, and IIIB (with DL). Each subgroup was then evaluated at two time points: T1 (after two weeks) and T2 (after eight weeks), with eight teeth assessed at each interval.

Surgical Induction of Class V Cavities and Pulp Capping Procedures

Dogs were premedicated with an intramuscular injection of xylazine (0.5 mg/kg; Xyla-Ject, Adwia Pharmaceuticals, Egypt), nalbuphine HCl (1 mg/kg; Nalufin, Amoun Pharmaceutical Company), and atropine sulfate (0.04 mg/kg; Memphis Pharmaceutical). Following premedication, general anesthesia was induced via intravenous administration of propofol (2 mg/kg; Diprivan, AstraZeneca). Anesthesia was maintained using a combination of 2% isoflurane (IsoFlo, Zoetis) and oxygen. (30). The teeth were isolated using a rubber dam, and disinfected with 2% chlorhexidine. A Class V cavity was prepared on the cervical third of the labial surface using a high-speed contra-angle handpiece fitted with a 1.5 mm round bur (Figure 1). Pulpal exposure was achieved, and dentinal debris was removed by irrigation with normal saline. Hemostasis was obtained by applying cotton pellets moistened with 2.5% sodium hypochlorite (29). In group I, high-purity Teflon sheets (Chemours™, Wilmington, Delaware, USA) were used. These sheets were precision-cut into uniform discs measuring 0.5–1 mm in thickness and 1.5 mm in diameter to fit the prepared Class V cavities. The discs were sterilized by autoclaving and stored in sterile packaging to maintain aseptic conditions. In Group II, the pulp exposure sites were capped with MTA (Angelus, Londrina, Paraná, Brazil), prepared at a 3:1 powder-to-liquid ratio according to the manufacturer's instructions. After 30 seconds of mixing to achieve a sandy consistency, the MTA was applied using a specialized applicator to ensure proper coverage and sealing. Group III involved the application of Well-Root PT (Vericom Co., Ltd., Chuncheon, Korea) in premixed capsule form, using a dedicated applicator gun. A plastic instrument was used to apply a precise amount over the exposed pulp, ensuring adequate sealing and protection.

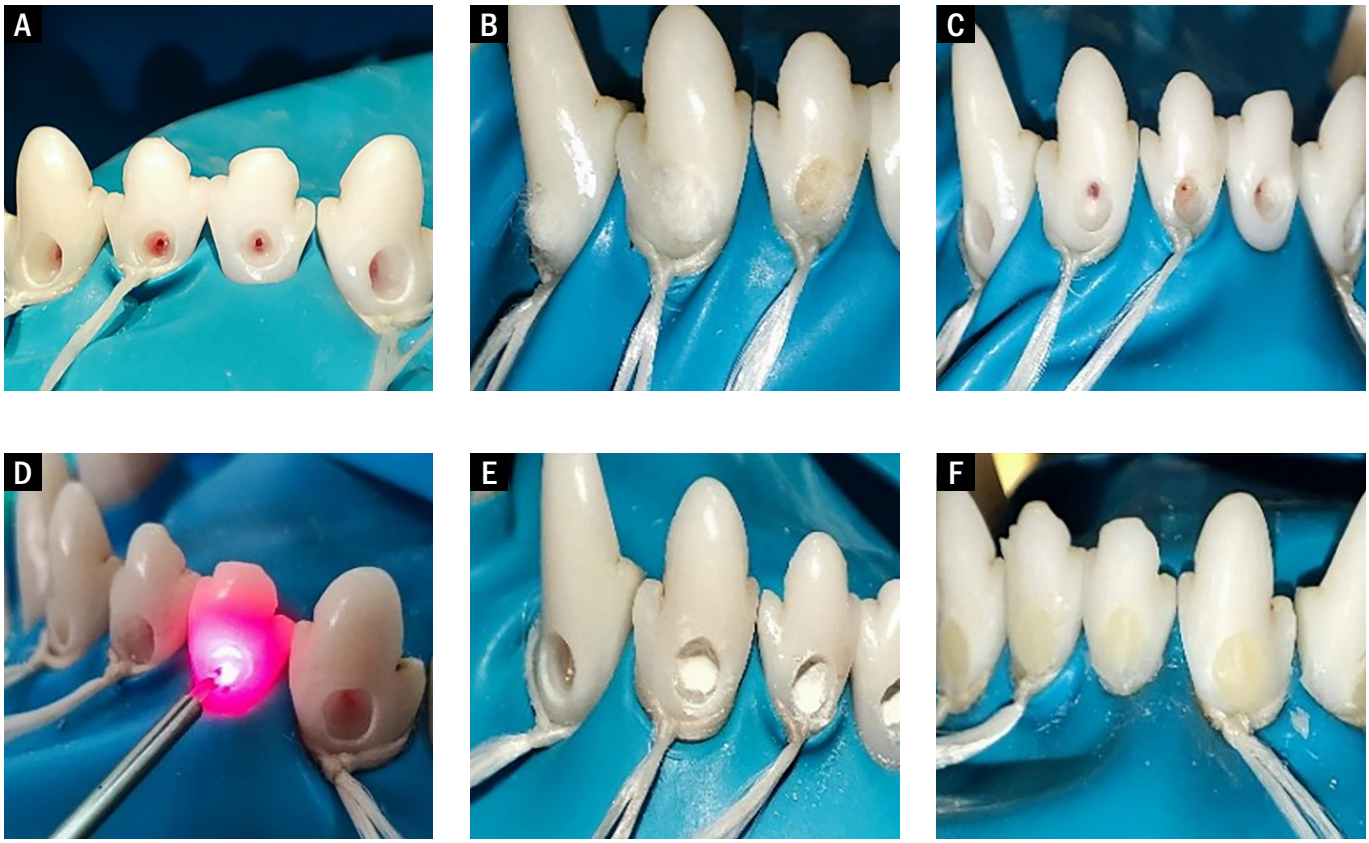

Figure 1
Clinical steps of the direct pulp capping procedure. (**A**) Cavity preparation; (**B**) application of sodium hypochlorite for disinfection; (**C**) bleeding control; (**D**) diode laser application; (**E**) placement of the capping material; and (**F**) restoration with glass ionomer cement.

Application of DL

In the subgroups designated to receive DL treatment, the exposed pulp areas were irradiated with the DL prior to the application of the capping material. The DL operated at a wavelength of 810 nm in continuous wave mode, delivering a power output of 20 mW. It was manually positioned approximately 2 mm from the exposure site to ensure precise targeting (Figure 1). Irradiation was performed for 150 seconds, covering a spot size of approximately 0.2 cm^2.
Considering an estimated 50% energy loss through the nozzle, the actual energy delivered to the tissue was calculated to be 1.5 J, resulting in an energy density of 7.5 J/cm^2. Following DL application, pulp capping was performed, and all cavities were then restored using a light-cured resin-modified glass ionomer cement (GC Fuji II, GC Corporation, Japan) (29).

Postoperative management

All dogs received intramuscular meloxicam (0.2 mg/kg daily for 3 days) for postoperative pain management. Throughout the experiment period, the oral cavity was closely monitored for signs of inflammation, swelling, discharge, or restoration failure. Regular examinations were performed to ensure the integrity of the treated teeth.

Samples Preparation and Histological Evaluation

After two weeks, four dogs were humanely euthanized (31), followed by the remaining four after eight weeks. Vital perfusion was performed, and the teeth along with surrounding tissues were block-sectioned and fixed in 10% formalin. The samples were then decalcified using 17% EDTA over a period of six months and subsequently embedded in

paraffin. Using a microtome, the paraffin-embedded tissues were sectioned buccolingually into slices measuring 4–6 µm in thickness. The sections were stained with hematoxylin and eosin (H&E) for histological analysis and were coded for blinded evaluation.
For the interpretation of histopathological changes in the pulp tissue, each section was evaluated and graded according to criteria adapted from the scoring system proposed by Domínguez et al. (32). This system assessed four key outcomes: dentin bridge formation, the quality of the dentin within the bridge, the degree of pulpal inflammation, and the tissue response to the capping material as indicated in Table 1.

Statistical analysis

Statistical analysis was performed using SPSS version 26.0 (IBM Corp., Armonk, NY, USA). The Shapiro–Wilk test was used to assess data normality. Associations between categorical variables were evaluated using the Chi-square test. Paired sample t-tests were applied for within-group comparisons over time, while one-way ANOVA followed by Bonferroni post hoc tests was used for comparisons between groups.

Results

Dentin Bridge Formation

At both the two-week and eight-week observation periods, dentin bridge formation was more evident in Group II (MTA) and Group III (Well-Root PT) compared to the control group (Group I). Statistical analysis revealed a significant difference between Group I and both Group II and Group III at the two-week interval ($P = 0.0018$), while no significant difference was observed between Group II and Group III ($P = 0.7212$) (Table 2). A calcific barrier covering more than 75% of the exposure site (grade 4) was observed in 62.5% and 87.5% of Group II and Group III, respectively. In contrast, 75% of Subgroup IA and 62.5% of Subgroup IB exhibited no dentin bridge formation (grade 0) (Figure 2). Similarly, at the eight-week interval, a significant difference was found between Group I and both Group II and Group III ($P = 0.0023$), with no

Table 1
Criteria and Scoring System Used for Histological Analysis

Criteria	Score	Description
Dentin bridge formation	0	Absence of dentin bridge formation
	1	Equal to 25%
	2	More than 25% and up to 50%
	3	More than 50% and up to 75%
	4	More than 75%
Quality of the dentin formed within the bridge	0	Absence of tubules
	1	Irregular tubules pattern
	2	Irregular tubules pattern
Pulpal inflammation	1	No inflammation
	2	Minimal inflammation
	3	Moderate inflammation
	4	Severe inflammation
	5	Abscess formation
	6	Tissue necrosis
Tissue reaction to the material	0	No macrophages and/or multinucleated giant cells adjacent to material.
	1	Mild-to-moderate infiltration of macrophages and/or multinucleated giant cells.
	2	Moderate infiltration of macrophages and/or multinucleated giant cells.
	3	Severe infiltration of macrophages and/or multinucleated giant cells.

Score	Experimental subgroups						P-value (between groups)	P-value (between Group II and III)
	IA	IB	IIA	IIB	IIIA	IIIB		
	n=8	n=8	n=8	n=8	n=8	n=8		
Dentin bridge formation								
0	75%	62.5%	0%	0%	0%	0%	0.0018**	0.7212
1	25%	12.5%	0%	0%	0%	0%		
2	0%	25%	0%	0%	0%	0%		
3	0%	0%	37.5%	25%	25%	12.5%		
4	0%	0%	62.5%	75%	75%	87.5%		
Intra-group comparison between DL and non-DL subgroups)	0.297		0.589		0.521			
Quality of formed dentin bridge								
0	75%	62.5%	0%	0%	0%	0%	0.0003**	0.5153
1	25%	37.5%	100%	87.5%	87.5%	75%		
2	0%	0%	0%	12.5%	12.5%	25%		
Intra-group comparison between DL and non-DL subgroups	0.589		0.301		0.521			
Pulpal inflammation								
1	0%	0%	0%	25%	12.5%	37.5%	0.017**	0.7153
2	0%	12.5%	12.5%	62.5%	75%	62.5%		
3	12.5%	25%	25%	12.5%	12.5%	0%		
4	12.5%	12.5%	12.5%	0%	0%	0%		
5	50%	37.5%	37.5%	0%	0%	0%		
6	25%	12.5%	12.5%	0%	0%	0%		
Intra-group comparison between DL and non-DL subgroups	0.770		0.716		0.351			
Tissue reaction to the capping material								
0	0%	0%	12.5%	25%	12.5%	37.5%	0.0011**	0.6846
1	0%	12.5%	62.5%	62.5%	75%	62.5%		
2	25%	25%	25%	12.5%	12.5%	0%		
3	75%	62.5%	0%	0%	0%	0%		
Intra-group comparison between DL and non-DL subgroups	0.579		0.716		0.351			
Significant level P<0.05								

Table 2
Percentage Distribution of Histologic Parameters in Each Experimental Subgroup at the Two-Week Observation Period

significant difference between Group II and Group III (P = 1.00) (Table 3). All samples in the MTA and Well-Root PT groups demonstrated complete calcific bridge formation (grade 4). In contrast, 75% of Subgroup IA and 62.5% of Subgroup IB still showed no evidence of dentin bridge formation (Figure 3). The application of DL had no statistically significant effect on dentin bridge formation in any of the subgroups at any observation period.

Dentin Bridge Quality

Atubular structure persisted in the major-

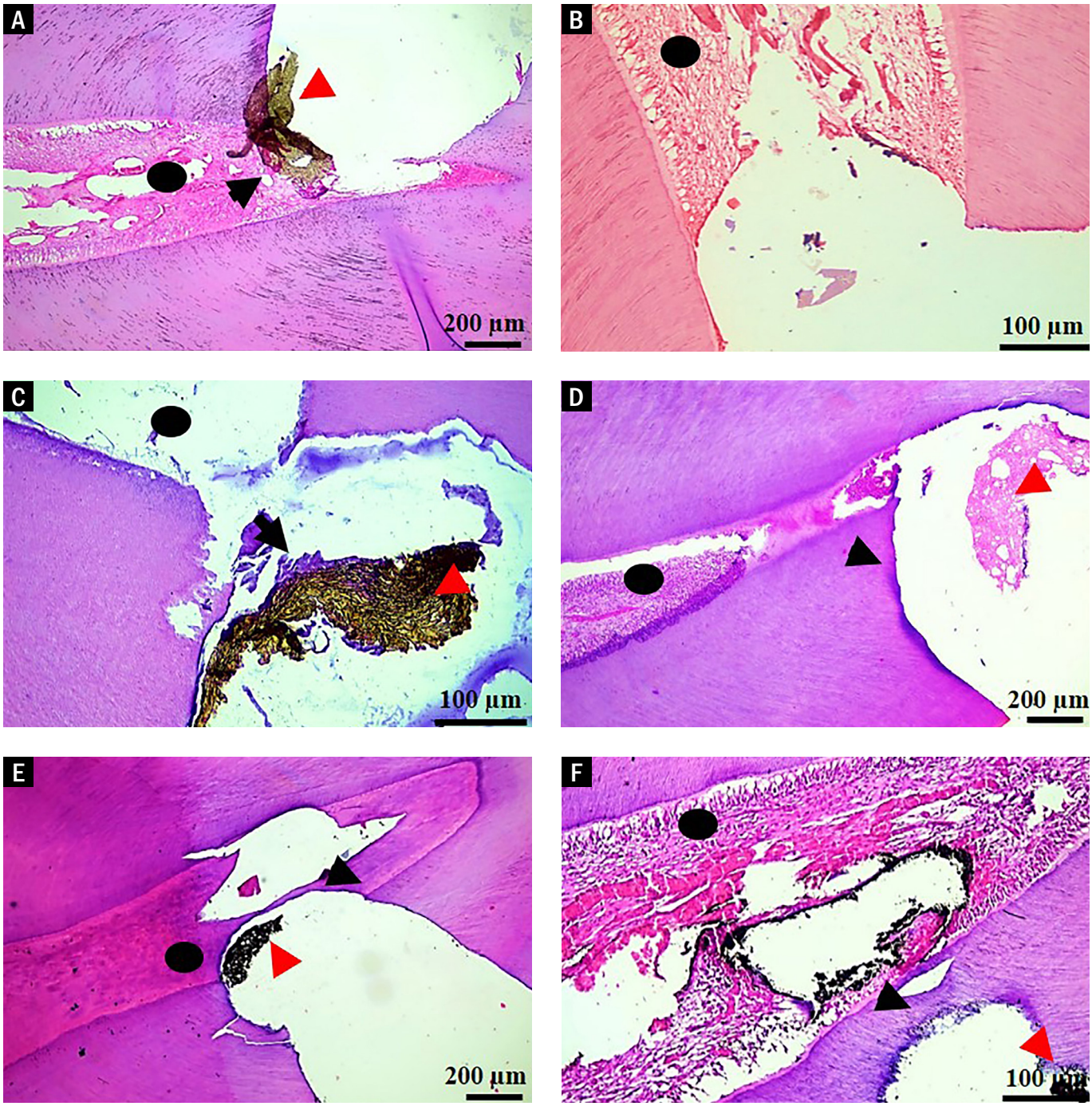

Figure 2
Representative microscopic images after two weeks of direct pulp capping. Figures A, C, and E correspond to subgroups IA, IIA, and IIIA, respectively, while figures B, D, and F represent subgroups IB, IIB, and IIIB, respectively. (**A**) showed degeneration of some odontoblasts, pus formation, and incomplete calcific barrier formation (<25%) associated with pulpitis. (**B**) revealed degeneration of pulp tissue with vasodilation. (**C**) demonstrated partial formation of a dentin bridge. (**D**) showed irregular dentin bridge formation accompanied by moderate pulpitis and calcific barrier formation. (**E**) revealed complete calcific barrier formation in the dentin bridge. (**F**) showed complete calcific barrier formation of a dentin bridge with impaction of Well-Root PT into the pulp tissue and the formation of a double bridge. The black circle represents the pulp tissue, the black arrow represents the dentin bridge, and the red arrow represents the capping material.

Score	Experimental subgroups						P-value (between groups)	P-value (between Group II and III)
	IA	IB	IIA	IIB	IIIA	IIIB		
	n=8	n=8	n=8	n=8	n=8	n=8		
Dentin bridge formation								
0	75%	62.5%	0%	0%	0%	0%	0.0023**	1
1	12.5%	12.5%	0%	0%	0%	0%		
2	12.5%	12.5%	0%	0%	0%	0%		
3	0%	12.5%	0%	0%	0%	0%		
4	0%	0%[a]	100%	100%	100%	100%		
Intra-group comparison between DL and non-DL subgroups)	0.779		1.00		1.00			
Quality of formed dentin bridge								
0	75%	62.5%	0%	0%	0%	0%	0.0012**	0.7212
1	25%	37.5%	87.5%	75%	75%	62.5%		
2	0%	0%	12.5%	25%	25%	37.5%		
Intra-group comparison between DL and non-DL subgroups	0.589		0.521		0.589			
Pulpal inflammation								
1	0%	0%	50%	87.5%	50%	87.5%	0.005**	0.3326
2	0%	0%	25%	12.5%	37.5%	12.5%		
3	0%	12.5%	25%	0%	12.5%	0%		
4	25%	25%	0%	0%	0%[b]	0%		
5	50%	37.5%	0%	0%	0%[b]	0%		
6	25%	25%	0%	0%	0%[b]	0%		
Intra-group comparison between DL and non-DL subgroups	0.766		0.206		0.244			
Tissue reaction to the capping material								
0	0%	0%	50%	87.5%	50%	87.5%	0.001**	0.3326
1	0%	12.5%[a]	25%	12.5%	37.5%	12.5%		
2	12.5%	37.5%	25%	0%	12.5%	0%		
3	87.5%	50%	0%	0%	0%	0%		
Intra-group comparison between DL and non-DL subgroups	0.244		0.206		0.244			
ignificant level P<0.05								

Table 3
Percentage Distribution of Histologic Parameters in Each Experimental Subgroup at the Eight-Week Observation Period

ity of control subgroups IA and IB (75% and 62.5%, respectively) at both two weeks and eight weeks, with no change over time. Meanwhile, irregular tubular patterns remained predominant in subgroups IIA, IIB, IIIA, and IIIB (87.5%, 75%, 75%, and 62.5%, respectively), although an increase in regular tubular dentin formation was observed (12.5%, 25%, 25%, and 37.5%, respectively) at the eight-week observation period.

Statistical analysis revealed significant differences between Group I and both Group II and Group III over time. The P-values (0.0003 at two weeks and 0.0012 at eight weeks) indicated that the scores were not randomly distributed across the groups. However, no significant differ-

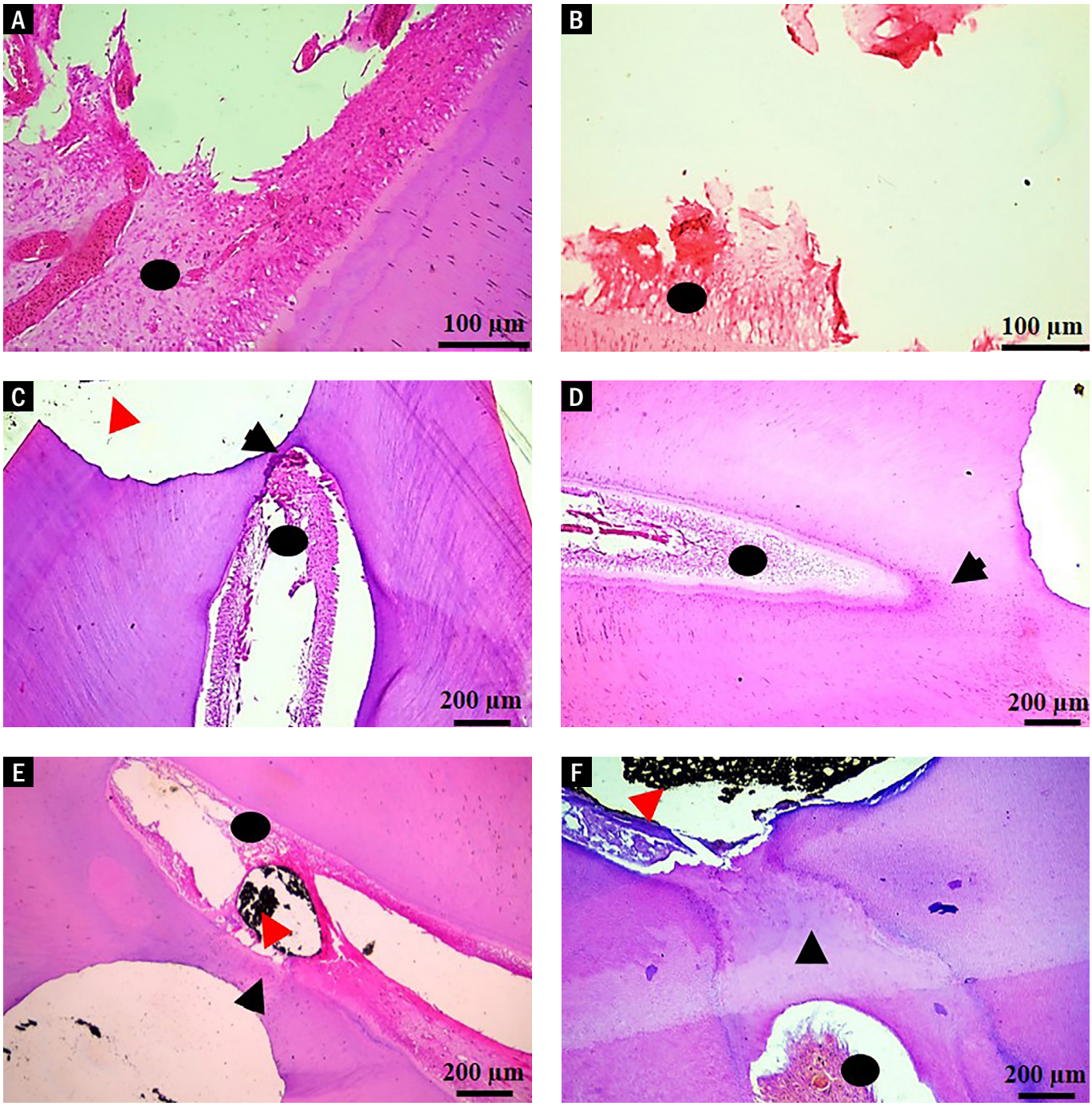

Figure 2
Representative microscopic images after eight weeks of direct pulp capping. Figures A, C, and E represent subgroups IA, IIA, and IIIA, while figures B, D, and F correspond to subgroups IB, IIB, and IIIB. (**A**) showed loose parts of the pulp, severe inflammation, and marked vasodilatation with the formation of granulation tissues. (**B**) revealed complete loss of pulp tissue. (**C**&**D**) demonstrated complete calcific barrier formation of the dentin bridge. (**E**) revealed complete calcific barrier formation of a dentin bridge with impaction of Well-Root PT into the pulp. (**F**) showed complete and thick calcific barrier formation of a dentin bridge with irregular dentin and Well-Root PT material. The black circle represents the pulp tissue, the black arrow represents the dentin bridge, and the red arrow represents the capping material.

ence was found between Group II and Group III (P = 0.5153).

Pulpal Inflammation and Tissue Reaction to the Capping Materials

At both the two-week and eight-week observation periods, statistically significant differences in pulpal inflammation were found between Group I and both Group II and Group III (P = 0.017 and 0.005, respectively). However, no significant differences were observed between Group II and Group III at the same time points (P = 0.3326 and 0.7153, respectively) (Table 2 and 3). Accordingly, the tissue response to the capping materials followed a consistent pattern, with statistically significant differences observed between Group I and both Group II and Group III at both time points (P = 0.0011 at two weeks and P = 0.001 at eight weeks). In contrast, no significant differences were found between Group II and Group III at either time point (P = 0.6846 and P = 0.3326, respectively).

At the two-week interval (Figure 2), mild pulpal inflammation (grade 1), accompanied by vasodilation of blood vessels, was observed in most samples from subgroups IIA, IIB, IIIA, and IIIB. Meanwhile, the control group (subgroups IA and IB) exhibited severe inflammatory responses, including pulp necrosis and degeneration of the odontoblast layer. Vasodilation and marked inflammatory cell infiltration were frequently observed in most cases (grades 4, 5, and 6). Granulation tissue formation was also significantly more pronounced in the control subgroups compared to Groups II and III ($P < 0.05$).

At eight weeks (Figure 3), the subgroups of Group II and Group III exhibited either no inflammation or only mild signs, with an absence of inflammatory infiltrates, macrophages, and multinucleated giant cells. Blood vessels were either mildly enlarged or appeared normal (grades 0 and 1). Conversely, the control group continued to exhibit a high incidence of pulpitis, with frequent observations of marked vasodilation, dense inflammatory cell infiltration, and granulation tissue formation. Marked pulpal necrosis was also evident, characterized by extensive odontoblastic degeneration, disorganization of the remaining degenerated cells, and significant narrowing of the pulp space.

Discussion

Direct pulp capping is a vital pulp therapy procedure designed to preserve the integrity and vitality of the pulp tissue. The present study demonstrated that dentin bridge formation was minimal in the absence of a pulp capping material, with less than 25% observed at two weeks and only a slight increase at eight weeks. This limited healing response can be attributed to the lack of bioactive stimulation and insufficient protection against microbial invasion (33, 34). On the other hand, the application of bioactive materials such as MTA and Well-Root PT significantly enhanced dentin bridge formation. Both MTA and Well-Root PT showed comparable efficacy, with more than 50–75% dentin bridge formation by two weeks and complete bridge formation in all samples by eight weeks. These materials are known to release calcium ions and stimulate odontoblastic differentiation, contributing to their regenerative potential (35, 36). Regarding DL application, the study found no statistically significant difference in dentin bridge formation between groups treated with and without laser use. This indicated that the primary role of DL may lie in its disinfection capability rather than direct stimulation of dentinogenesis (29). Meanwhile, Alharbi et al. (28) have reported improved regenerative outcomes with DL application, particularly when used in combination with EndoSequence Root Repair Material. These discrepancies may be attributed to differences in laser protocols, including wavelength, exposure time, and frequency. Overall, the present findings revealed the critical role of bioactive pulp capping materials in promoting dentinogenesis, while the adjunctive use of DL remains inconclusive.

Structurally, dentin bridges observed at

two weeks exhibited primarily irregular tubular patterns, with no significant differences between MTA and Well-Root PT or between laser-treated and non-laser-treated subgroups. However, by eight weeks, regular tubular structures became more evident across all groups. These results indicate that both materials support progressive dentinogenesis and mineralization in a controlled environment, aligning with prior findings (37, 38). The DL influence appeared to be limited to bacterial reduction rather than altering the structural characteristics of the dentin bridge, which may explain the absence of significant variation between laser-treated and non-treated samples (38).

Contrary to the present findings, Sivadas et al. (39) reported improved dentin bridge quality following DL application, which may be attributed to variations in the pulp capping materials used. Some studies have suggested that DL enhanced dentin bridge formation (28, 40), while others, such as Al-Agele et al. (41), emphasized its role in pulp healing rather than mineralization. These conflicting outcomes highlight the variability in experimental designs, laser parameters, and material-laser interactions. Overall, the results of this study support the notion that the type of pulp capping material plays a more critical role in dentin bridge formation and structure than adjunctive laser therapy. Concerning the pulpal status, the absence of a capping material resulted in severe inflammation, abscess formation, and progressive pulp necrosis over time. Conversely, both MTA and Well-Root PT significantly reduced inflammation and showed mild to moderate levels at two weeks and minimal or absent inflammation at eight weeks. These effects can be attributed to the materials' alkaline pH, calcium ion release, and sealing ability, all of which contribute to pulp healing and reduced bacterial colonization (42). In this study, no significant differences were observed between MTA and Well-Root PT in terms of pulpal response, further supporting existing evidence that Well-Root PT is a viable alternative to MTA. The use of DL was associated with a slight reduction in pulpal inflammation prior to capping; however, these effects were not statistically significant. The photobiomodulatory effects of DL can stimulate cellular activity and tissue repair, variability in laser parameters may influence their clinical outcomes (43). Consistent with the observed pulp status, the tissue reaction to the capping materials was characterized by the presence of macrophages and multinucleated giant cells during the first two weeks following pulp capping, with their numbers decreasing significantly by eight weeks. No significant differences were observed between MTA and Well-Root PT, regardless of DL application. In contrast, the control group exhibited persistent inflammation, pus formation, and, in many cases, complete pulp loss. The reduction in immune cell presence over time reflects the natural healing process and is consistent with the known biocompatibility of both MTA and Well-Root PT (44). These findings align with previous studies that reported minimal long-term inflammatory responses when using bioactive capping materials, further reinforcing their critical role in promoting pulp repair and healing (45, 46). The limitations of the current study include a relatively small sample size and a limited observation period of eight weeks, which may not reflect long-term outcomes such as the stability of the dentin bridge and sustained pulp vitality. Additionally, the use of a single DL protocol limits the understanding of how different laser settings might influence healing. Future research should include longer follow-up periods, larger sample sizes, and clinical trials to validate these findings. Further studies should also explore various DL parameters and compare newer bioceramic materials to determine the most effective approach for long-term pulp regeneration.

Conclusion

This study concluded that Well-Root PT is an effective and clinically comparable alternative to MTA for direct pulp cap-

ping, showing similar efficacy in promoting dentin bridge formation and preserving pulp vitality. The use of DL did not significantly improve treatment outcomes, indicating that its primary role may be limited to disinfection rather than directly enhancing tissue regeneration. These findings emphasize that the choice of a biocompatible, bioactive capping material is the most critical factor in the success of direct pulp capping, outweighing any additional benefit from DL application.

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Conflict of interest statement
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Author Contributions
Mo'men A. Salama: writing – review and editing, writing – original draft, validation, methodology, investigation, formal analysis, data curation, and conceptualization. Dalia M. Fayyad: writing – review and editing, writing – original draft, validation, supervision, investigation, and conceptualization. Mohamed I. Rabie: writing – review and editing, writing – original draft, validation, supervision, investigation, and conceptualization. Manar A. A. Selim: writing – review and editing, supervision, investigation, and conceptualization. Mahmoud F. Ahmed: writing – review and editing, methodology, validation, supervision, investigation, resources, and conceptualization.

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