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Success Rate of Direct Pulp Capping with Conventional Procedures Using Ca $(OH)_2$ and Bioactive Tricalcium Silicate Paste vs. Laser-Assisted Procedures (Diode 980 nm, CO_2, and Er: YAG)

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Abstract: Direct pulp capping (DPC) is reliable in pulp exposure management. Objective: This study aimed to assess the success rate of DPC materials and different laser protocols. The included procedures were CO_2 laser (n = 1147), Er: YAG laser (n = 69), and 980 nm diode laser (n = 124), on the one hand, and Ca $(OH)_2$ (n = 376) and bioactive tricalcium silicate paste, on the other (n = 279). Materials and methods: Data from 1995 DPC cases were included. For laser groups, irradiation was used to coagulate the pulp exposure followed by Ca $(OH)_2$ placement. Data with follow-up at 12, 24, and 36 months post-treatment were included. The irradiation parameters for the CO_2 laser were as follows: energy density per pulse of 141 J/cm^2, 1 W power, 0.3 mm beam diameter, 100 ms pulse duration, and 1 Hz, and a series of five pulses maximum were delivered during 5 s. For the 980 diode lasers: 1.5 W power, continuous wave (CW), 400 µm fiber diameter, contact mode, 190.98 W/cm^2 power density, and total delivered energy density of 2387 J/cm^2. For the Er: YAG laser: 0.5 W output power, 9.95 J/cm^2 energy density, a beam diameter of 0.8 mm, 300 µsec pulse duration, 10 Hz, non-contact mode, irradiation with air without water spray, and an average irradiation time of 8–10 s. Results: At the 3-year follow-up, the success percentages were as follows: CO_2 (88.01%) > Ca $(OH)_2$ (75.72%) > diode (70.01%) > Er: YAG (54.55%) > bioactive tricalcium silicate paste (51.1%). The timing of permanent filling (immediate or delayed), patient age, size of pulp exposure, tooth type, and exposure etiology significantly affected the success rate. Patients aged $\leq$ 35 years presented higher success (70.91%) compared to those $\geq$ 36 years (61.2%). Immediate permanent fillings increase the success rate (71.41%) compared to delayed permanent fillings (65.93%). Exposure in molars and premolars significantly lowers the success rate (60.3%) compared to canines and incisors (72.1%). Idiopathic pulp exposure presented higher success (72.58%) compared to caries-related causes (63.7%). Conclusion: The highest success rate was in the CO_2 laser group followed by the diode and Ca $(OH)_2$, Er: YAG, and bioactive tricalcium silicate material (biodentine) groups. The age factor, filling timing, size of exposure, tooth type, and exposure etiology can significantly affect the success rate of DPC.

Keywords: endodontics; disinfection; restorative dentistry; laser; pulp exposure; pulp capping

1. Introduction

The success of a direct pulp capping treatment and the preservation of dental vitality increases the longevity of teeth and prevents their loss. Pulp exposure during restorative dental procedures such as caries excavation and crown preparation is relatively frequent [1,2]. Depending on the situation, pulpotomy, pulpectomy, indirect pulp capping, or direct pulp capping (DPC) are the treatment modalities. Concerning DCP, these procedures are indicated at the same session of exposure and during mechanical cavity preparation or immediately after trauma [3] and must only be made on a vital tooth having no history of spontaneous pain, mobility, apical reaction, or signs of necrosis at the exposure site [3,4]. Several materials have been described in the literature for the management of DPC, such as calcium di-hydroxide Ca $(OH)_2$, mineral trioxide aggregate (MTA), formocresol, and bioactive tricalcium silicate cements (Biodentine) [4–7].

The primary objective of direct pulp capping (DPC) is to establish a resilient protective barrier, commonly referred to as a newly formed dentinal bridge, over the exposed pulpal tissue. This dentinal bridge plays a crucial role in preserving the vitality of the tooth [8–11]. Under favorable circumstances, the damaged odontoblasts can trigger the migration of stem cells from the pulpal tissue to the site of the pulp exposure, where they undergo differentiation into odontoblast-like cells [12–15]. Remarkably, the formation of this dentinal bridge is made possible by the innate regenerative potential of the dental pulp [8–11].

The success of DPC treatment is known to be dependent on various conditions and factors. One crucial factor is the extent of hemorrhage and/or the dimensions of the exposed pulp surface, as they are directly proportional to the failure of DPC. In simpler terms, a smaller hemorrhage and exposure size increase the likelihood of success [16]. Additionally, several uncontrollable factors have been linked to the success rate of DPC treatment, including the location of the exposure, the arch site, the patient's age, the etiology of the pulp exposure, and whether a permanent filling is placed immediately or with delay, among others [17,18].

On the other hand, the choice of materials used in direct pulp capping is also critical for treatment success, and this aspect can be controlled by the operator. Pulp capping materials must possess biocompatibility, strong antibacterial properties, relatively fast setting time, and soft compressive strength, and should not cause pulp compression during the capping procedure [19,20]. Among these materials, calcium dihydroxide (Ca $(OH)_2$), mineral trioxide aggregate (MTA), formocresol, and bioactive tricalcium silicate cements (such as Biodentine) have garnered significant attention [21,22].

To enhance the success rate of DPC procedures, the utilization of lasers as adjuncts to conventional direct pulp capping methods has been proposed in the literature [23–28]. The use of lasers has shown improved results, attributed to various factors such as the potential for direct blood coagulation at the exposed site, the antimicrobial effects of irradiation, and the stimulation of pulpal repair and regeneration [23–28]. Nevertheless, there remains a significant gap in knowledge regarding the impact of different wavelengths and irradiation parameters on the success rate and long-term outcomes of laser-assisted protocols.

Therefore, the aim of this retrospective study was to assess the success rate of direct pulp capping protocols with different capping materials and laser-assisted protocols. Data collection of DPC with calcium di-hydroxide Ca $(OH)_2$, mineral trioxide aggregate (MTA),

CO_2 laser (10,600 nm), 980 nm diode laser, and Er: YAG laser (2940 nm) was performed with three years of follow-up for each clinical case. The null hypothesis was that there is no significant difference in the success rate of direct pulp capping between different protocols.

2. Materials and Methods

2.1. Study Design and Participants

This multicenter retrospective study was carried out with data collected in the period between 1990 and 2022. Data collection was only performed for all direct pulp capping treatments made with one of the following direct pulp capping materials and/or laser-assisted direct pulp capping procedures: Ca $(OH)_2$, tricalcium-silicate-based paste, carbon dioxide laser (CO_2 with 10,600 nm wavelength), diode laser (980 nm) and Erbium-doped yttrium aluminum garnet laser (Er: YAG with 2790 nm wavelength). The decision for direct pulp capping was made after informing all patients about the steps of the pulp capping treatment that was suggested. Moreover, any possible complication, postoperative discomfort, or failure of the treatment was discussed with the patient. A total of 1995 cases of DPC were included in this retrospective study. Enrolled patients had a mean age of 32 years (min: 10; max: 69), with 39.75% being female (n = 793) and 60.25% male (n = 1202), and with cavity classification and teeth position recorded (Table 1). Among the 1995 cases, 376 sites were treated with Ca $(OH)_2$, 279 were treated with bioactive tricalcium silicate paste (n = 279), 1147 were treated with the CO_2 laser (n = 1147), 124 were treated with the diode (980 nm) laser (n = 124), and 69 were treated with the Er: YAG laser (n = 69) (Table 2). All included patients signed a written informed consent before enrollment. Our retrospective study based on data collection cannot be considered a new clinical study and therefore did not legally require prior approval from the ethical committee of the University of Liege.

Table 1. Relevant clinical features of the included teeth (n = 1995).

Number of Treated Teeth	Sex		Age Range (Years)	Patients: Age ≤ 35 Years	Patients: Age ≥ 35 Years	Clinical Size of Exposed Pulp (Range in mm)		Cavity Classification		Tooth Position	
	Male	Female	Avg: 32 Min: 10 Max: 69	Avg: 16 Min: 10; Max: 35	Avg: 44 Min: 36; Max: 69	Size of Exposed Pulp ≤ 1 mm	Size of Exposed Pulp >1 mm and <2 mm	Occlusal	Proximal	Incisor and Canine	Premolar and Molar
1995	1202 (60.25%)	793 (39.75%)	1995	1044	951	1163	832	664	1331	471	1524

Avg = average; min = minimum; max = maximum; mm = millimeters.

Table 2. Distribution of clinical cases according to different procedures.

	Procedure					
	Ca $(OH)_2$ Paste	Bioactive Tricalcium Silicate Paste	CO_2	Er: YAG	Diode	Total
Number of teeth	376	279	1147	69	124	1995

2.2. Different Pulp Capping Protocols

In all clinical cases, local anesthesia was used, and a rubber dam was placed at each pulp exposure site before DPC treatment. The exposed pulp of fractured teeth caused by trauma was not included in our data. The size of the exposed pulp was estimated using a periodontal probe (PCP UNC 15, HuFriedy, Chicago, IL, USA). Then, laser treatment of exposed pulp or the conventional procedure was performed. The conventional protocol consists of Ca $(OH)_2$ paste application to cover all the exposed pulp and a part of the persisting dentin surrounding the exposed area followed by the placement of glass ionomer. On the other hand, the bioactive tricalcium silicate paste was placed to cover all the exposed pulp and the rest of the bottom of the cavity. Afterward, and as a function of the time availability for the treatment by each practitioner, there were two possibilities: to place the permanent filling of composite material (immediate permanent filling) at the same session or to wait until an average of 6–8 weeks after pulp capping and then place the permanent composite filling (delayed filling) (Table 3). For the groups of calcium hydroxide and of laser-assisted protocols (CO_2 laser group, 980 nm diode laser group, and Er: YAG laser group), laser irradiation was performed prior to the application of Ca $(OH)_2$.

Table 3. Distribution of clinical cases according to the tooth site in all groups.

Teeth	Immediate Permanent Fillings	Delayed Permanent Fillings	Total
Number of teeth	1249	746	1995

2.2.1. Calcium Hydroxide Ca $(OH)_2$ Paste (*n* = 376)

Calcium dihydroxide paste (multi-cal calcium hydroxide paste, Pulpdent, Watertown, MA, USA) was used. After exposure, a sterile cotton pellet was gently placed without pressure for one minute to control the pulp bleeding. Afterward, a layer of Ca $(OH)_2$ covering all the exposure areas and a part of the surrounding dentin was placed. A decision for either delayed filling or immediate permanent filling was made according to the description in Section 2.2.

2.2.2. Bioactive Tricalcium Silicate (*n* = 279)

Bioactive tricalcium silicate (Biodentine™, Septodont, Saint-Maur-des-Fossés, France) was used. The bioactive tricalcium silicate was applied respecting the manufacturer's recommendations. When the pulp was exposed, a sterile cotton pellet was gently placed without pressure to control pulp bleeding for one minute followed by a layer of bioactive tricalcium silicate covering the entire pulp exposure area and the bottom of the cavity. After a waiting time of 15 min to allow the hardening of the bioactive tricalcium silicate, a decision for either delayed filling or immediate permanent filling was made according to the description in Section 2.2.

2.2.3. Carbon Dioxide (CO_2) Laser (*n* = 1147)

When a pulp exposure occurred, irradiation with a CO_2 laser was performed to coagulate the bleeding in non-contact and pulsed mode at the focal distance of 10 mm. The parameters were an energy density per pulse of 141 J/cm^2, power of 1 W, beam diameter of 0.3 mm (0.03 cm), pulse duration of 100 ms (0.1 s), and 1 Hz, and a series of 5 pulses maximum were delivered for 5 s. If needed, another series of 5 pulses can be emitted after a wait of 30 s between series. Then, a layer of Ca $(OH)_2$ paste was placed to cover the pulp exposure and a small part of the surrounding dentin (0.5–1 mm), aiming to assure a biocompatible direct contact between the treated exposed pulp and the filling material. A decision for either delayed filling or immediate permanent filling was made according to the description in Section 2.2.

2.2.4. The 980 nm Diode Laser (*n* = 124)

The same clinical steps and procedure applied with the CO_2 laser were applied for the 980 nm diode laser but with different parameters, as follows: a power of 1.5 W, in continuous mode (CW), a fiber diameter of 400 µm, non-initiated and in contact and swiping mode, a sterile tip angle set to 90°; an average of 2 s total delivered energy density of 2387 J/cm^2 were sufficient to provoke coagulation on the exposed pulp. A decision for either delayed filling or immediate permanent filling was made according to the description in Section 2.2.

2.2.5. Er: YAG Laser (Erbium-Doped Yttrium Aluminum Garnet Laser) (*n* = 69)

The same clinical steps and procedure applied with the CO_2 laser were applied to the Er: YAG laser but with different parameters. An Er: YAG laser with 2940 nm was used but under an output power of 0.5 W, energy of 50 mJ, energy density per second of 9.95 J/cm^2, beam diameter at target tissue of 0.8 mm, pulse duration of 300 µs, 10 Hz as the number of pulses per second, total irradiation time of 1 to 3 s, and in non-contact mode with air and without water. The aim was to coagulate the exposed pulp. Afterward, Ca $(OH)_2$ was applied to cover the exposed pulp. A decision for either delayed filling or immediate permanent filling was made according to the description in Section 2.2.

2.3. Inclusion and Exclusion Criteria

Data collection included clinical pulp capping respecting the following inclusion criteria:

2.3.1. Inclusion Criteria

- Permanent teeth with deep caries;
- Vital teeth confirmed by vitality test;
- No spontaneous pain (only provoked pain);
- No periapical radiographic changes (Figure 1);
- No periodontal problems for the tooth in question;
- Acceptance of the research program and guidelines.

The following criteria were respected to exclude clinical cases from our data collection:

2.3.2. Exclusion Criteria

- Symptoms of dental discomfort related to the teeth in question;
- Periapical radiographic changes;
- Bleeding continued for more than 3 min after pulp exposure;
- Pulp exposure larger than 2 mm;
- Spontaneous and prolonged pain, and pain disturbing night sleep;
- Fractured teeth with exposed pulp due to trauma;
- Patients were taking corticosteroids;
- Lack of acceptance of the study's guidelines;
- Pregnancy.

2.4. Follow-Up and Evaluation of the Success

The collected data included the follow-ups at twelve months (T12), twenty-four months (T24), and thirty-six months (T36) after treatment. Pulp vitality was tested with (1) ethyl chloride cold test (Coltene, Henry Schein, New York, NY, USA), (2) vertical and horizontal percussion test, (3) apical palpation pressure test, and (4) electric pulp vitality test (Digitest II tooth vitality tester, Parkell Inc., New York, NY, USA). These four pulp vitality tests were considered as the qualitative data (Table 4). The cold test was first used to assess the vitality of the pulp. If the cold test gave a negative result, an electric vitality test, horizontal and vertical percussion test, apical pressure test, and X-rays were performed to reach a decision on whether a normal state of pulp or a pathological state was then considered. In addition, similar examinations were performed during each follow-up session to confirm the diagnosis of clinical examination and to assess the presence of any secondary signs of treatment failure, namely periapical radiographic changes, loss of pulp vitality and reaction, or the appearance of secondary caries at the treated cavity. Therapies on teeth that remained asymptomatic, with positive vitality tests and no radiographic signs of periapical pathology, were considered clinical successes (Table 4).

Table 4. Qualitative evaluation criteria for the pulp sensitivity tests.

Test	Normal State of the Pulp Tissue	Pathological State of Pulp Tissue		
		Reversible Pulpitis	**Irreversible Pulpitis**	**Necrosis**
Cold test with ethyl chloride	Positive (no change in intensity or duration after stimulation)	Positive (with change in intensity and/or duration less than 5 s after stimulation)	Positive (with change in intensity and/or duration more than 5 s after stimulation)	Negative
Horizontal percussion test	Negative	Negative	----	positive
Vertical percussion test	Negative	Negative	----	Positive
Apical palpation pressure	Negative	Negative	----	Positive
Electric vitality test	Positive	Positive	Positive	Negative

2.5. Statistical Analysis

The dependent variable in all the analyses was specified as 'success at last follow-up'. The Kaplan–Meier analysis and log-rank test were used to calculate the cumulative success proportion and mean time. Prognostic clinical variables were also identified with univariate Cox proportional hazard regression analysis. Post hoc analyses were performed according to the survival of the teeth in both groups using the NCSS Trial and PASS 2000 programs (http://www.ncss.com/download/pass/free-trial). The number of patients follows the minimal criteria for achieving a power of 90% and an effect size of 0.3. Standard parameters including a significance level of 0.05, d value = 0.3, 95% confidence interval, and 90% power of the study were used to calculate the minimal sample size for our groups using G×Power software (Kiel University, Kiel, Germany).

All the data of our groups were evaluated using normality tests for normal distribution (the D'Agostino–Pearson and Kolmogorov–Smirnov tests) and the analyses were performed using SPSS software version 20.0 (IBM SPSS Inc., Chicago, IL, USA). Two-way repeated measures ANOVA coupled with the Bonferroni post-test were performed to assess the significance of the difference between groups. All hypothesis tests were two-tailed and performed at a significance level of 0.05.

3. Results

The CO_2 laser group consistently demonstrated the highest success rate throughout the follow-up period, surpassing all other groups with statistically significant differences. After twelve months of treatment, the CO_2 laser group exhibited the highest success rate (90.1%), followed by the diode laser 980 nm group (80.5%) and the Ca $(OH)_2$ group (79.81%). The success rates for the Er: YAG laser group (60.58%) and the bioactive tricalcium silicate group (58.6%) were comparatively lower. Notably, no statistically significant difference was observed between the 980 nm diode laser group and the Ca $(OH)_2$ group, indicating similar levels of success. The Er: YAG and bioactive tricalcium silicate groups yielded the least successful outcomes, but no statistically significant difference was found between these two groups. At the thirty-six-month follow-up, the CO_2 laser group maintained the highest success rate at 88.01%, followed by the Ca $(OH)_2$ paste group (75.72%), the diode laser 980 nm group (70.01%), the Er: YAG laser group (54.55%), and the bioactive tricalcium silicate group (51.1%). Notably, a significant difference was observed between all the success rates at the thirty-six-month follow-up period. The null hypothesis was rejected. A difference in success rates between groups was observed. It was also noted that laser-assisted DPC results in a higher success rate when compared to conventional methods only when the CO_2 laser was used. From highest to lowest, the success rate was as follows: CO_2 laser > Ca $(OH)_2$ > diode laser > Er: YAG laser > bioactive tricalcium silicate (Table 5 and Figure 1).

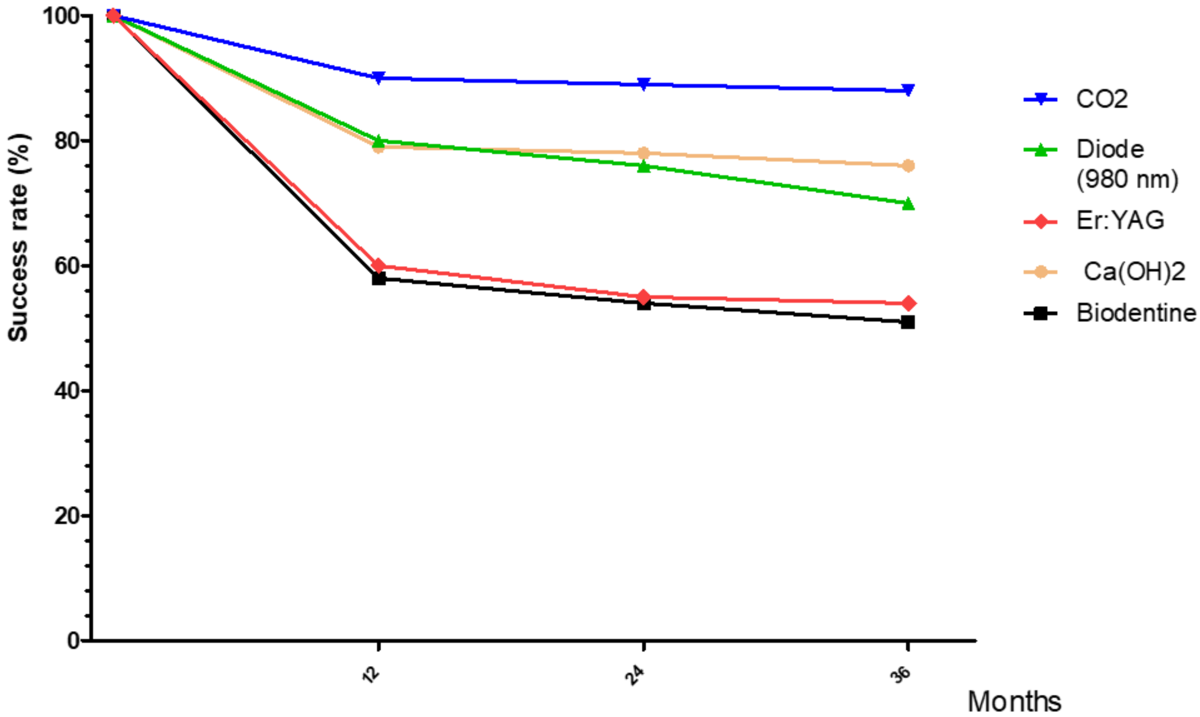

Figure 1. Success rate related to different pulp capping procedures during the follow-up period.

Table 5. Cumulative success rate and standard deviation (percentage) related to different follow-up periods.

Period (Months)	Ca $(OH)_2$ (Paste)	Bioactive Tricalcium Silicate	Diode Laser (980 nm)	CO_2 Laser	Er: YAG Laser
Twelve months	79.81% ^{A}	58.6% ^{C}	80.5% ^{A}	90.10% ^{G}	60.58% ^{C}
Twenty-four months	78.09% ^{A}	54.32% ^{D}	76.56% ^{B}	89.86% ^{G}	55.42% ^{D}
Thirty-six months	75.72% ^{B}	51.1% ^{E}	70.01% ^{F}	88.01% ^{G}	54.55% ^{D}

Identical letters indicate the absence of a statistically significant difference, while different letters indicate a statistically significant difference. p-value < 0.0001.

Cumulative Results Related to Other Factors

The results of this retrospective data collection revealed that the timing of permanent filling, the age of the patient, the tooth type (premolar, molar, canine, and incisor), and the cause of pulp exposure can significantly affect the success rate and can be considered as relevant factors. Patients aged ≤ 35 years presented a statistically higher success rate (70.91%) than patients aged > 36 years (61.2%) (Table 6 and Figure 2). Moreover, the immediate placement of a permanent filling resulted in an increased success rate (71.41% $\pm$ 2.53%) when compared to the placement of a permanent filling after 6–8 weeks (65.93% $\pm$ 2.7%). In addition, pulp exposure in molars and premolars presented a lower DPC success rate (60.3%) when compared to pulp exposure on canines and incisors (72.1%). Also, idiopathic pulp exposure presents higher DPC success rates (72.58%) when compared to caries-related causes of pulp exposure (63.7%) (Table 6 and Figure 2).

Table 6. Cumulative global success rate and standard deviation at 36 months post-op in all groups (%) and all treated cases (n = 1971 cases) related to the age range, immediate or delayed permanent filling, teeth sites, and the cause of pulp exposure at the 36-month follow-up.

Immediate Permanent Fillings	Delayed Permanent Fillings (6–8 Weeks)	Patients: Age ≤ 35 Years	Patients: Age > 35 Years	Pulp Exposure on Molars and Premolars	Pulp Exposure on Canines and Incisors	Idiopathic and Accidental Pulp Exposure	Caries-Caused Pulp Exposure
71.41 ± 2.53% ^{A}	65.93 ± 2.7% ^{B}	70.91 ± 3.4% ^{A}	61.2 ± 1.4% ^{C}	60.3 ± 2.2% ^{D}	72.1 ± 1.7% ^{E}	72.58 ± 2.66 ^{E}	63.7 ±1.7% ^{F}

Identical letters indicate the absence of a statistically significant difference, while different letters indicate a statistically significant difference.

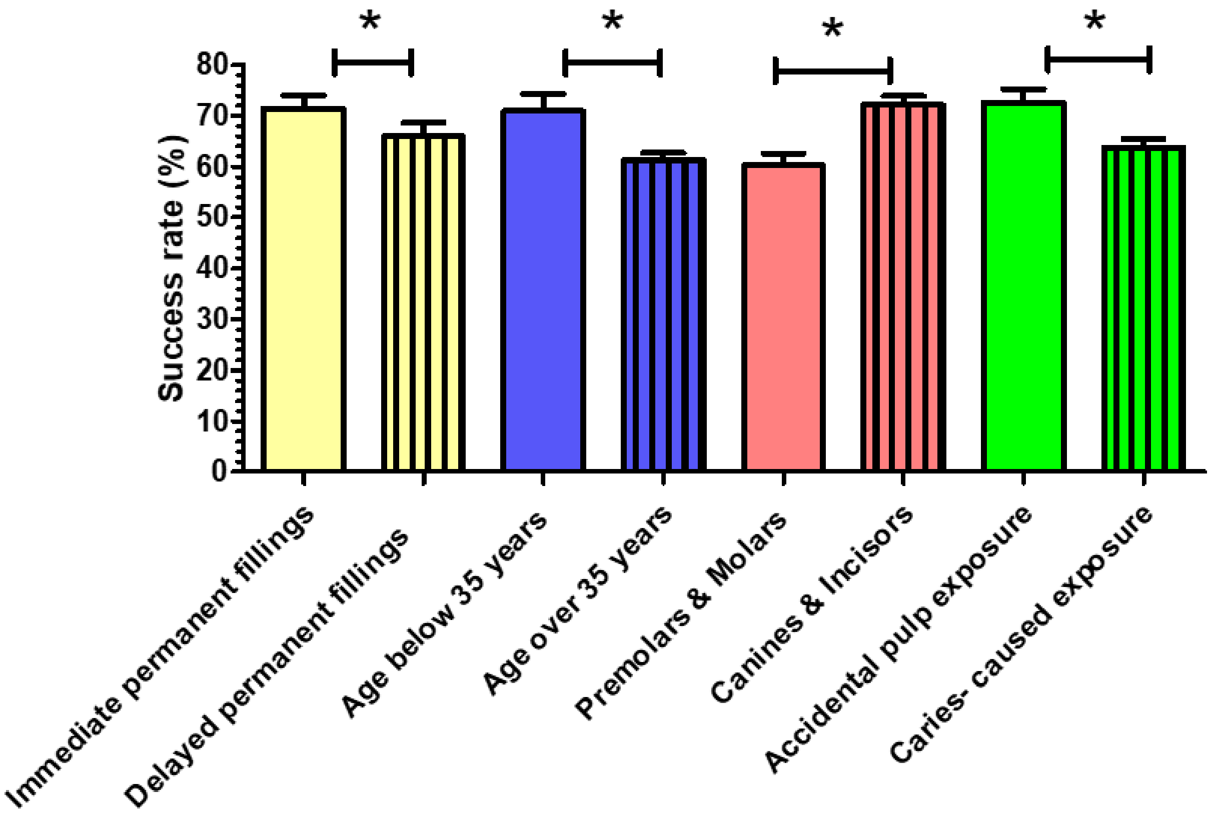

Figure 2. Success rate (%) of pulp capping related to different variables: Age, fillings, teeth, and exposure causes. * indicates a statistically significant difference between groups.

4. Discussion

In this retrospective study, data collection and analysis were conducted on two main factors: the impact of different treatment protocols and the influence of various variables such as age, etiology of pulp exposure, size of exposure, tooth type, and the timing of permanent filling placement. Regarding conventional direct pulp capping (DPC), after a 3-year period, calcium hydroxide (Ca $(OH)_2$) exhibited a higher success rate (75.72%) compared to bioactive tricalcium silicate paste (51.1%). Not all laser-assisted protocols demonstrated a superior success rate when compared to the conventional application of Ca $(OH)_2$. Specifically, only the use of a CO2 laser resulted in a significantly higher success rate compared to the application of Ca $(OH)_2$ alone. In this study, it should be noted that there exists some variance in the number of participants between each group, which may introduce potential implications for the overall generalizability of the findings. It is important to highlight that the retrospective data collection was conducted across multiple institutions. Consequently, the decision to utilize or abstain from using the laser treatment was not based on specific findings or individual cases. This approach reduces the potential for bias or the influence of specific circumstances that may have influenced the choice to administer the laser treatment.

Regarding the variables evaluated in this retrospective study, it was observed that patients under the age of 35 exhibited an overall higher success rate for DPC (approximately 70.91%) compared to patients older than 35 (approximately 61.2%). This finding is somewhat expected as younger pulp chambers and apices tend to be wider and possess richer vascularization, which is more favorable for the healing or regenerative process [29]. In fact, younger pulpal tissue possesses superior regenerative properties due to its higher cell count, increased levels of fibroblast growth factor (FGF), growth factor-β (TGF-β), platelet-derived growth factor (PDGF), and greater presence of anti-inflammatory mediators [30–34]. Furthermore, it was observed that idiopathic exposures exhibited a higher success rate (72.58%) when compared to caries-related exposures (63.7%). It has been well established that a tooth is more likely to survive direct pulp capping (DPC) if the initial exposure is caused by mechanical factors rather than caries. This association stems from the fact that caries penetration into the pulp leads to bacterial invasion of the pulp by the tubules, resulting in heightened and prolonged pulpal inflammation. Consequently, the pulp's responsiveness is diminished, compromising its healing potential, unlike in cases of mechanical exposure where preexisting inflammation and bacterial infiltration are absent [35–41].

Our study confirmed that if used properly, the CO_2 laser can effectively facilitate DPC, thereby increasing the treatment's success rate [42–44]. Irradiation with the CO_2 laser offers sufficient disinfection to the exposed pulp and the dentinal tubules in its vicinity [45–48]. Indeed, the antibacterial properties inherent in the laser beam can provide significant advantages in enhancing disinfection prior to the application of the capping material [45–48]. This will result in a "less contaminated environment", leading to favorable conditions for pulpal wound regeneration. Besides disinfection, the laser beam can stop pulp bleeding and seal small blood vessels by thermal coagulation [23,49]. This increased control of bleeding will decrease the severity of the inflammation. Hence, it seems that the coagulation of the exposed pulp produced by the CO_2 laser includes a thin layer of coagulated and less infected tissues, below which there is an area where the injury can be reversed, inducing the migration of stem cells, inflammatory cells, and fibroblasts [50,51]. This may have ultimately contributed to the dentinal bridge formation. In addition to disinfection and coagulation, the biostimulation effect of the laser beam may be valuable in DPC [52,53]. In fact, this biostimulation effect can modulate the overall inflammatory process by accelerating and stimulating the proliferation and migration of the pulp cells, cytodifferentiation of odontoblast-like cells, synthesis of the dentin extracellular matrix, and formation of reparative dentin in the injured pulp tissue [53,54].

The effectiveness of laser-assisted protocols is supported in the literature. Hasheminia et al. [54] conducted a histological study on the healing process following laser irradiation, demonstrating the formation of well-formed dentin lined with odontoblastic cells, especially in the area where blood extravasation had occurred. Furthermore, the histological study revealed a normal morphological appearance of the pulp following laser-assisted DPC [54].

Furthermore, this three-year follow-up evaluation settled which wavelength provides the best treatment outcome in the long term. This difference in the success rate may be explained by analyzing the laser–tissue interaction. In fact, each wavelength is absorbed differently by the targeted tissues (pulp and surrounding dentin) [55–57]. The absorption of the laser energy by water or by a specific chromophore and its penetration depth depends on its wavelength. In fact, different wavelengths produce different morphological modifications on the surface of the pulp and its surrounding dentinal tissue, including vaporization, carbonization, homeostasis, protein denaturation, and coagulation [57]. This may have led to a difference in the disinfection and coagulation potential, leading to a difference in the success rate. As a matter of fact, when lasers were used, the highest percentage of success was obtained with the 10,600 nm CO_2 laser (88.01%) followed by the 980 nm diode laser (70.01%), and the lowest was obtained with the Er: YAG laser (54.55%).

This may be explained by the highest capacity of the CO_2 laser to superficially coagulate pulp tissue and to melt dentin and infected tubules, because of its high absorption by hydroxyapatite and water, higher than those of the diode and Er: YAG lasers. Moreover, the Er: YAG laser has an explosive effect on tissues and generates less heat which may produce less coagulation on exposed pulp.

It seems that the CO_2 laser with its 10,600 nm wavelength has several advantages over the others. For instance, the irradiation with the CO_2 laser seems to result in a generation of heat that is enough to coagulate the blood without deep tissue penetration, probably leaving it in a decent condition for better regeneration. In addition, the CO_2 laser's potent ability of dentinal fusing might have led to better disinfection of the dentinal tubules surrounding the exposure site [58,59]. This capacity of dentinal disinfection is particularly important in carious exposures when the surrounding tubules are contaminated by microorganisms. In accordance with this hypothesis, Melcer et al. [50] showed in a histological study that a rich vascularized granulation tissue in full cellular activity can be observed under the coagulum of the exposed pulp with the CO_2 laser. This cellular activity reabsorbed the coagulum and led to complete healing. In addition, Melcer et al. [50] noted significant odontoblastic activity with a dentinogenetic formation on the side of the coagulated pulp exposure which eventually led to the closure of the pulp exposure by a newly formed dentinal bridge. Also, in accordance with our hypothesis, an experimental study on dogs conducted by Nammour et al. [24] showed that with CO_2 laser-assisted DPC, 10 weeks post-op, a thicker dentinal bridge (±391.5 μm) formed compared to the typical dentinal bridge obtained with conventional DPC with Ca $(OH)_2$ (±294.1 μm) [24]. They suggested that CO_2 laser irradiation may enhance the pulp regeneration potential and dentinal bridge formation.

In our study, the use of the 980 nm diode laser prior to the Ca $(OH)_2$ did not show an improvement in the success rate compared to Ca $(OH)_2$ alone. This seems to be attributable to the relatively significant heat produced by the 980 nm diode laser. As Robinson and Letkowitz stated [60], "Excessive heat is the most serious single insult to the pulpal tissue". Therefore, when the 980 nm wavelength of the diode laser was used to coagulate the exposed pulp, a slight increase in temperature (10 °F or 12.22 °C) could have resulted in serious destruction of the pulp tissues and could have led to a spatial derangement and pyknosis of the diminished remainder [60]. Hence, we suggest that further studies should use the 980 nm diode laser but in pulsed or super-pulsed mode to decrease the propagation of heat since in our study the irradiation was performed in continuous mode [61–63]. Concerning the results obtained with the Er: YAG laser, it seems that the wavelength presents two relative drawbacks when it comes to DPC: its low potential of coagulation and its micro-explosive effect [64,65]. The micro-explosive effect was somehow managed by decreasing the energy to 50 mJ and by working in defocused mode. However, this might have led to partial and superficial coagulation that might not have been of good quality for the regeneration and/or disinfection of the dentinal tubules. Therefore, the effectiveness of the exposed pulp coagulation might have been reduced and the success rate decreased.

As already mentioned, laser-assisted protocols in DPC are well studied in the literature [66–69]. In a meta-analysis, Deng et al. [66] concluded that the use of the CO_2 and Er: YAG lasers improves the prognosis of DPC with an 89.9% success rate [66], while in our retrospective study, the prognosis of DPC improved only when the CO_2 laser was used [68]. Wang et al. [43] studied the use of the Er: YAG laser with Ca $(OH)_2$ and showed that this combination results in a higher success rate (91.7%); however, unlike our study, the follow-up period was only 12 months [43]. On the other hand, Hasheminia et al. [54] performed a histological study comparing MTA, Er: YAG laser + MTA, and Er: YAG laser + Ca $(OH)_2$ and found no significant difference in terms of inflammatory response or pulp tissue condition [54]. Clinically, Zhang et al. [68] revealed that the success rate (89.4%) increases when a diode laser is used in combination with Ca $(OH)_2$. Zhang et al. included 50 patients with carious-related pulp exposure, and the success rate of the conventional DPC method was only 73.3% [70]. As for the CO_2 laser, Moritz et al. [23], concluded based on 200 DPC procedures that the CO_2 laser is a valuable aid in direct pulp capping since at the 12-month follow-up, 89% of patients presented a successful treatment while only 68% had a successful treatment in the conventional group [23]. A study by Zafari et al. [71] investigated the combined effect of dental dressing materials and low-level laser therapy (LLLT) on the viability of stem cells from apical papillae and subsequent dental regeneration. The results showed that combinations of MTA, enamel matrix derivative (EMD), and LLLT as well as bioactive tricalcium silicate paste, EMD, and LLLT, significantly increased the viability of stem cells from apical papillae [69]. Overall, the study suggests that LLLT in combination with effective dental capping materials holds promise in DPC [69]. In addition, Alsofi et al. concluded in a study that LLLT in combination with EndoSequence root repair material shortens the inflammatory phase and enhances the healing [44], and Alharbi et al. [70] showed that LLLT combined with bioactive ERRM is effective in inducing reparative dentin formation [70]. Moreover, it is interesting to note that in our study, the success rate achieved with the 980 nm diode laser combined with Ca $(OH)_2$ was lower compared to Yazdanfar et al.'s study [28], where they reported a 100% success rate using the 810 nm diode laser. This disparity may be attributed to several factors in our study, including a larger sample size, longer follow-up duration, and the utilization of a 980 nm diode laser, whereas Yazdanfar et al. [28] employed an 810 nm laser. These variations in sample size, follow-up period, and laser wavelength may account for the observed differences in success rates between the two studies.

Going through the results in the literature, it can be noted that the success rate varies between studies. This difference can be attributed to the fact that different irradiation parameters are used in different studies. Ca $(OH)_2$ indeed has the longest track record of clinical success and remains the "gold standard" pulp capping material. In our retrospective study, Ca $(OH)_2$ (63.82%) had a superior success rate compared with bioactive tricalcium silicate (51.1%). Despite being an excellent antimicrobial material, Ca $(OH)_2$ also has a relatively fast setting time, which can be a significant advantage when compared to bioactive tricalcium silicate paste. The higher success rate of Ca $(OH)_2$ may probably be explained by the longer period of high PH production in comparison to bioactive tricalcium silicate, resulting in a greater disinfection effect and probably higher anti-inflammatory potential. However, it is important to note that, unlike our findings, a meta-analysis and systematic review by Cushley et al. [71] found, with low-quality evidence, that better long-term outcomes were obtained with MTA and bioactive tricalcium silicate compared to Ca $(OH)_2$ in DPC for permanent teeth with caries-caused exposed pulps. Based on our findings and on the literature, it may be interesting to evaluate, in future research, the clinical outcomes associated with the utilization of photobiomodulation (PBM) as an additional procedure at the conclusion of dermal papilla cell treatment.

5. Conclusions

Within a three-year follow-up, it can be concluded that in direct pulp capping, irradiation with a CO_2 laser before the conventional application of Ca $(OH)_2$ significantly increases the success rate of DPC. Moreover, the use of the 980 nm diode and Er: YAG lasers showed a lower success rate when compared to the conventional application of Ca $(OH)_2$ alone, revealing that the use of these wavelengths negatively affected the success of DPC when combined with the conventional application of Ca $(OH)_2$. Additionally, the lowest success rate was obtained with bioactive tricalcium silicate.

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