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Lasers efficacy in pain management after primary and secondary endodontic treatment: a systematic review and meta-analysis of randomized clinical trials

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Postoperative pain is a common concern following root canal treatments (RCT), impacting both patients and oral health practitioners. This systematic review and meta-analysis aimed to evaluate the effectiveness of laser treatment modalities in reducing postoperative pain compared to conventional methods after primary and secondary RCT in permanent mature teeth. A search of three electronic databases (PubMed, ScienceDirect, and The Cochrane Library) was conducted, using a broad range of keywords and terms. Gray literature and manual searches were conducted to complement the search. The inclusion criteria included randomized clinical trials based on the objective of the secondary study. A minimum sample size of 10 participants per group and a clearly defined criterion for postoperative pain assessment were required. The characteristics of the included studies were presented as tables. The Cochrane collaboration tool RoB 2.0 was used to assess the risk of bias within each study. Two reviewers extracted the data and assessed the studies independently, and discrepancies were resolved through consultation with a third reviewer. A random-effects model was employed for meta-analysis to estimate the overall effect measure. Heterogeneity was evaluated using Cochran's Q test and the I^2 index. Publication bias was explored via Funnel plots and Egger's test. Subgroup analyses and meta-regression were conducted to assess variations among laser methods and examine the influence of independent factors. The significance threshold for all analyses was set at 5% ($\alpha = 0.05$). Intraoral laser therapy demonstrated no significant advantage over conventional treatments but consistently outperformed placebo, particularly from 4 to 72 h post-treatment. Low-level laser therapy provided slight pain reduction in the first 8 h, though its effectiveness diminished in retreatment scenarios. Photodynamic therapy and laser disinfection showed marginal benefits, especially shortly after treatment, with reduced efficacy in longer-term or retreatment contexts. Further research is needed to explore different applications of laser modalities and assess distinct prognostic factors in more detail.

Keywords Dental laser applications, Dental pain, Dental pulp diseases, Diode laser, Endodontic pain relief, Endodontic treatment, Endodontically treated teeth, Endodontics, Laser therapy, Low-level laser therapy, Pain management, Periapical pain, Photobiomodulation, Photodynamic therapy, Postoperative pain, Root-filled teeth, Toothache, Root canal therapy

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Root canal treatment (RCT) is a dental procedure prescribed to address infected or damaged tooth pulp, involving the process of pulp removal, thorough root canal cleaning, shaping, precise filling, and a secure seal to prevent further infection[1,2]. One frequently encountered challenge following RCT is the occurrence of postoperative pain or flare-ups[3]. This discomfort originating from these endodontically-treated teeth (ETT) can arise from various factors, including lingering infection, inflammation, or irritation of surrounding tissues during the procedure[4,5]. Symptoms of postoperative pain commonly include discomfort, swelling, and mild to moderate pain[6,7].

Postoperative pain management after RCT comprises diverse strategies and interventions aimed at alleviating discomfort and pain arising after medical or surgical procedures[4,8]. These strategies fall into two primary categories: pharmacological and non-pharmacological approaches. Pharmacological options involve the use of non-steroidal anti-inflammatory drugs (NSAIDs)[9], acetaminophen[10], long-acting anesthetics[11], and intracanal medications[12]. While these pharmacological approaches offer benefits, oral health professionals must carefully consider the most suitable approach for individual patients while minimizing associated medication risks[13,14]. Consequently, the demand for non-pharmacological adjunct therapies, such as anxiety reduction protocols[15], cryotherapy[16], and intracanal laser therapy[17,18], has increased.

Among these adjunctive therapies for patients with ETT, laser and light-activated treatments have demonstrated remarkable versatility, offering a multitude of applications and methodologies[19,20]. These involve various treatments and techniques used to mitigate postoperative pain after endodontic procedures, including irrigation activation with Er: YAG lasers[21], canal disinfection utilizing Nd: YAG or diode lasers[17], photodynamic therapy (PDT)[22], and photobiomodulation (PBM) or low-level laser therapy (LLLT)[23]. Reported benefits of such therapeutic approaches involve different light wavelengths being absorbed by tissue chromophores, resulting in cyclooxygenase-2 suppression and enhanced clearance of pain-inducing substances[24,25]. Moreover, laser treatment influences plasma membrane permeability to ions like sodium, potassium, and calcium[26,27]. This modulation in permeability reduces C fiber activity while elevating neuron action potentials, offering a molecular explanation for post-laser pain reduction[26,27].

Previous reviews have examined the effects of laser treatments in endodontics, yet limitations exist in their scope and focus. Elafifi-Ebeid et al. (2023)[28] restricted their analysis to studies on initial RCT, excluding those on root canal retreatment (re-RCT), and concentrated solely on intracanal laser irradiation, omitting LLLT and PBM. Guerreiro et al. (2021)[29] included studies on LLLT but did not compare different laser treatment modalities, while Chen et al. (2019)[30] focused exclusively on LLLT without considering other laser therapies. Meire et al. (2023)[31] evaluated various adjunctive treatment modalities, such as ozone therapy and ultrasonically activated irrigation (UAI), without a sole emphasis on laser treatments. Lastly, Alonaizana & AlFawaz (2019)[32] examined the impact of PDT on postoperative endodontic pain management, but their systematic review had significant limitations, including a limited number of included studies and a qualitative analysis approach, and many of the clinical studies lacked specific control or comparison groups, making it challenging to determine the true impact. Therefore, the present systematic review aimed to assess the efficacy of various laser-dependent treatment modalities in diminishing postoperative pain subsequent to primary and secondary RCTs in comparison to conventional methods, according to the available randomized clinical trials and perform a meta-analysis.

Materials and methods

Protocol and registration

This systematic review is registered in the PROSPERO international prospective database of systematic reviews in health and social care under the registration identification number CRD42023415417. The secondary study adheres to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, ensuring comprehensive and transparent reporting[33].

Eligibility criteria

Population, Intervention, Comparison, Outcome, Timing, and Setting (PICOTS), were used to structure research questions and define key elements. The primary research question guiding this review is: "To what extent do various laser-dependent treatment modalities effectively reduce postoperative pain following both primary and secondary root canal treatments in comparison to conventional methods?".

Search strategy

An electronic search was conducted across three different databases: PubMed (National Center for Biotechnology Information, U.S. National Library of Medicine), ScienceDirect (Elsevier, Relx Group plc.), and The Cochrane Library (John Wiley & Sons, Ltd). This search was conducted without imposing any language or publication date restrictions, thus ensuring the inclusion of a broad spectrum of relevant literature. In addition, gray literature search was performed in three grey engines: CADTH's Grey Matters (https://greymatters.cadth.ca/), the European database on medical devices from the European Commission (https://ec.europa.eu/tools/eudamed/#/screen/home), and The New York Academy of Medicine Library (https://catalog.nyam.org/cgi-bin/koha/opac-search.pl).

A manual search complemented the search to ensure a thorough exploration and identification of relevant information. Two review authors (H.S and R.A) carried out the search process and study inclusion. In instances where a consensus was not readily reached between the two review authors, a third review author (F.E. or K.I.A.) served as an impartial arbitrator to resolve any discrepancies. The following search keywords were utilized to formulate the search strategy.

Eligibility criteria

Only randomized clinical trials comparing laser-dependent treatment modalities to conventional methods for reducing postoperative pain following primary or secondary root canal treatment were considered. The primary outcome of interest was postoperative pain, which had to be assessed using well-defined criteria. Inclusion criteria required a minimum sample size of 10 participants per group, and all interventions had to be performed on mature permanent teeth.

Data extraction

After reviewing the titles and abstracts of the search results, articles that potentially met the inclusion criteria were subjected to full-text examination. The following study characteristics and data were extracted: study name, sample size, age, sex, diagnosis, laser treatment method, instrument for documenting postoperative pain, pain scale measurement, anesthetic type, tooth type, and treatment type. Postoperative pain assessments were categorized into seven distinct time points: 4–6 h, 8 h, 12 h, 24–30 h, 48–72 h, 4–5 days, and 7 days post-treatment. Pain severity was further stratified into four levels using the quantitative data from the pain assessment instrument: no pain (0), mild pain (0.1–3.9) or (1–39), moderate pain (4-6.9) or (40–69), and severe pain (7–10) or (70–100). In cases of disagreement, consensus was achieved through discussions involving two review authors (H.S and R.A), with a third review author (F.E. or K.I.A.) providing resolution when needed.

Quality assessment

To assess the risk of bias, two review authors (H.S and R.A) independently conducted quality assessments for each of the included studies. Given that this review exclusively considered randomized clinical trials, the evaluation of bias risk followed The Cochrane Collaboration's RoB 2.0 tool[34]. Discrepancies were resolved through consultation with a third review author (F.E. or K.I.A.).

Statistical analysis

Our quantitative analysis comprised several key components, which included meta-analysis, heterogeneity analysis, publication bias assessment, and subgroup analysis. The meta-analysis was conducted using a random-effects model. This allowed us to estimate the overall effect measure, specifically the raw rate of patients experiencing null or mild pain, for both the laser and conventional treatment groups. To estimate heterogeneity, we utilized a restricted maximum likelihood estimator.

Our findings were visually represented using forest plots, complete with 95% confidence intervals. To further assess heterogeneity among the studies, we applied Cochran's Q test. Additionally, we calculated the I^2 index, which signifies the proportion of between-studies variability relative to the total variability. The funnel plot analysis was conducted to explore the potential presence of publication bias. To measure the impact of such bias, Egger's test was applied. Throughout the analyses, a significance level of 5% ($\alpha = 0.05$) was applied. We utilized R 3.5.1, a statistical computing software, for all calculations and data processing[35]. Subgroup analysis was undertaken for several comparisons:

Comparison between laser and control groups. Odds ratio (OR) was calculated as the effect measure, expressed as log OR due to its symmetric and normal characteristics. This analysis was conducted using a random-effects model, yielding corresponding Z statistics, p-values, and 95% confidence intervals, all visualized through forest plots.

Comparison between individual laser methods. We utilized the 'Log OR' from each study to assess the benefits of specific laser methods compared to their respective control groups. This standardized measure allowed for direct comparison between different articles. A mixed-effects model (meta-regression) was used with the moderator variable 'type of laser method.'

Effect of other factors. A meta-regression analysis was conducted using mixed-effects models to assess the influence of various moderator variables. These included mean age, gender distribution (% of males), anesthetic solution, tooth type (% in different positions), and the type of RCT. R^2 was calculated to quantify the extent to which each factor explained between-studies variability.

Results

Study selection

The study selection process was structured as depicted in Fig. 1 of the PRISMA flow diagram. Initially, the comprehensive literature search based on a strategy featuring including relevant keywords and MeSH terms (Table 1), resulted in a substantial pool of 7,288 studies aimed at addressing our focused research inquiry. To ensure the integrity of our dataset, diligent removal of duplicate entries was performed, resulting in the elimination of 7,198 redundant studies. Subsequently, the remaining studies underwent a rigorous assessment based on their titles and abstracts, applying the predefined inclusion criteria. Thereafter, this rigorous evaluation process culminated in the identification of 21 studies that merited comprehensive scrutiny through full-text analysis. Within this subset, four studies were deemed ineligible and were consequently excluded (Table 2). Ultimately, this qualitative synthesis encompassed a comprehensive review of the findings from the remaining 17 studies, which were included in the final qualitative synthesis.

Study characteristics

Summary of the included studies is presented in Table 3, comprising randomized clinical trials that compared the efficacy of laser-dependent treatment modalities to conventional methods for mitigating postoperative pain after both primary and secondary root canal procedures. The laser wavelength and activation protocols of the included studies are presented in Table 4. Among the various laser treatment modalities, PDT and PBM were most frequently investigated, appearing in 7 and 5 studies, respectively. Additionally, three studies examined

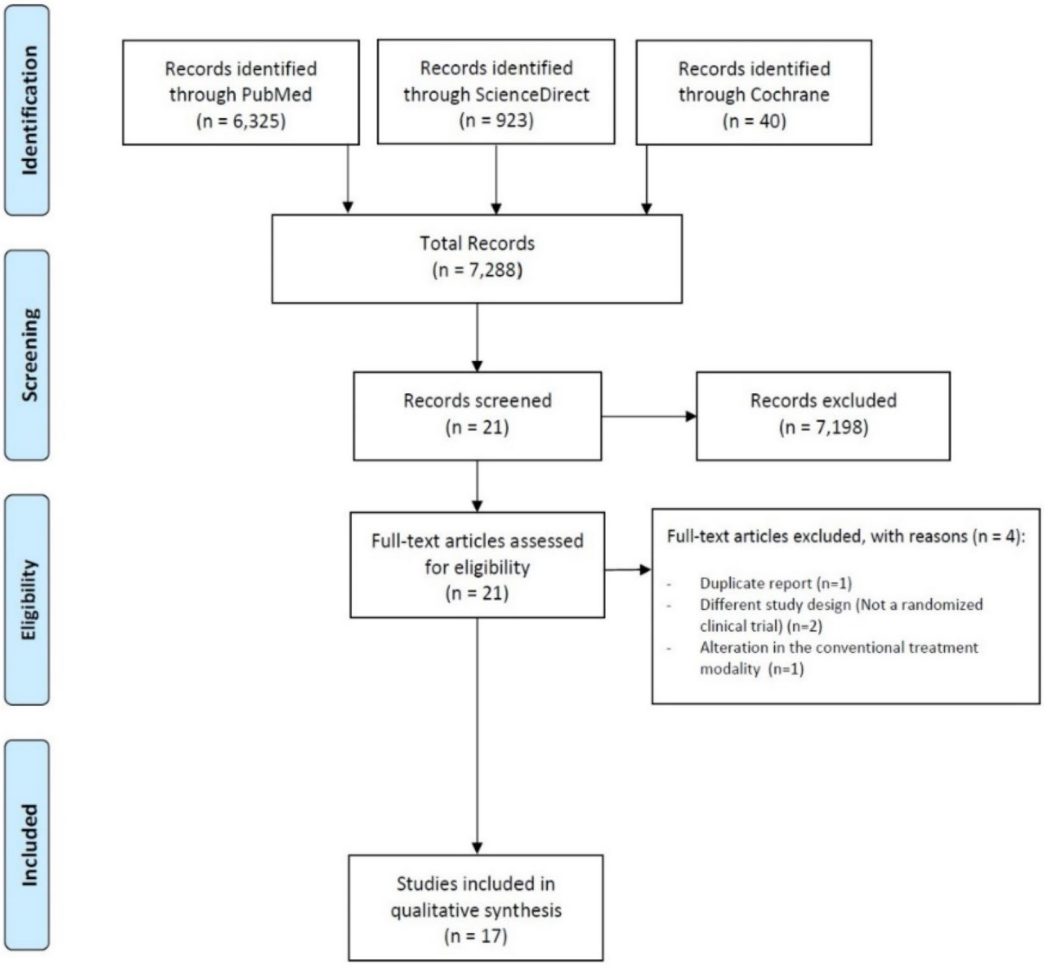

Fig. 1. PRISMA flow diagram: visual representation of the study selection process.

Field of exploration	Combination of keywords and terms
Laser AND Endodontics	("lasers"[All Fields] OR "lasers"[MeSH Terms] OR "lasers"[All Fields] OR "laser"[All Fields] OR "lasered"[All Fields] OR "lasering"[All Fields]) AND ("endodontal"[All Fields] OR "endodontic"[All Fields] OR "endodontical"[All Fields] OR "endodontically"[All Fields] OR "endodontics"[MeSH Terms] OR "endodontics"[All Fields])
Laser AND postoperative pain	("lasers"[All Fields] OR "lasers"[MeSH Terms] OR "lasers"[All Fields] OR "laser"[All Fields] OR "lasered"[All Fields] OR "lasering"[All Fields]) AND ("pain, postoperative"[MeSH Terms] OR ("pain"[All Fields] AND "postoperative"[All Fields]) OR "postoperative pain"[All Fields] OR ("postoperative"[All Fields] AND "pain"[All Fields]))
Laser AND endodontic treatment	("lasers"[All Fields] OR "lasers"[MeSH Terms] OR "lasers"[All Fields] OR "laser"[All Fields] OR "lasered"[All Fields] OR "lasering"[All Fields]) AND (("endodontal"[All Fields] OR "endodontic"[All Fields] OR "endodontical"[All Fields] OR "endodontically"[All Fields] OR "endodontics"[MeSH Terms] OR "endodontics"[All Fields]) AND ("therapeutics"[MeSH Terms] OR "therapeutics"[All Fields] OR "treatments"[All Fields] OR "therapy"[MeSH Subheading] OR "therapy"[All Fields] OR "treatment"[All Fields] OR "treatment s"[All Fields]))
Laser AND endodontic retreatment	("lasers"[All Fields] OR "lasers"[MeSH Terms] OR "lasers"[All Fields] OR "laser"[All Fields] OR "lasered"[All Fields] OR "lasering"[All Fields]) AND (("endodontal"[All Fields] OR "endodontic"[All Fields] OR "endodontical"[All Fields] OR "endodontically"[All Fields] OR "endodontics"[MeSH Terms] OR "endodontics"[All Fields]) AND ("retreat"[All Fields] OR "retreated"[All Fields] OR "retreating"[All Fields] OR "retreatment"[MeSH Terms] OR "retreatment"[All Fields] OR "retreatments"[All Fields] OR "retreats"[All Fields]))
Laser AND endodontic retreatment	("lasers"[All Fields] OR "lasers"[MeSH Terms] OR "lasers"[All Fields] OR "laser"[All Fields] OR "lasered"[All Fields] OR "lasering"[All Fields]) AND (("endodontal"[All Fields] OR "endodontic"[All Fields] OR "endodontical"[All Fields] OR "endodontically"[All Fields] OR "endodontics"[MeSH Terms] OR "endodontics"[All Fields]) AND ("retreat"[All Fields] OR "retreated"[All Fields] OR "retreating"[All Fields] OR "retreatment"[MeSH Terms] OR "retreatment"[All Fields] OR "retreatments"[All Fields] OR "retreats"[All Fields]))
Photodynamic therapy AND endodontics	("photochemotherapy"[MeSH Terms] OR "photochemotherapy"[All Fields] OR ("photodynamic"[All Fields] AND "therapy"[All Fields]) OR "photodynamic therapy"[All Fields]) AND ("endodontal"[All Fields] OR "endodontic"[All Fields] OR "endodontical"[All Fields] OR "endodontically"[All Fields] OR "endodontics"[MeSH Terms] OR "endodontics"[All Fields])
Photobiomodulation AND endodontics	"Photobiomodulation"[All Fields] AND ("endodontal"[All Fields] OR "endodontic"[All Fields] OR "endodontical"[All Fields] OR "endodontically"[All Fields] OR "endodontics"[MeSH Terms] OR "endodontics"[All Fields])

Table 1. Applied search strategy in PubMed/Medline electronic database.

Reasons for exclusion	Records
Duplicate report ($n=1$)	Brignardello-Petersen (2018)[36]
Different study design (Not a randomized clinical trial ($n=2$)	Barciela (2019)[37] Souza (2021)[38]
Alteration in the conventional treatment modality ($n=1$)	Nunes (2019)[39]

Table 2. Excluded articles and reasons for exclusion.

disinfection of the root canal system using Diode or Nd: YAG lasers, while two studies focused on irrigation activation with Er: YAG lasers.

Regarding the assessment of postoperative pain, the Visual Analogue Scale (VAS) emerged as the predominant instrument, as it was used in 12 out of the 17 studies. Other utilized instruments incorporated the Verbal Rating Scale (VRS), Numerical Rating Scale (NRS), Heft Parker pain survey, and evaluation of pain on percussion. These studies collectively form the basis for our comprehensive analysis of the effectiveness of laser-dependent treatment modalities in alleviating postoperative pain following root canal treatments.

Risk of bias assessment

The Cochrane collaboration tool RoB 2.0 was used to assess the risk of bias across the included studies. Of the 17 studies reviewed, 10 demonstrated an overall low risk of bias across all assessed domains (Fig. 2). In contrast, four studies received an assessment of "some concern" in specific domains, thus, were rated with an overall assessment of "some concerns."

Furthermore, three studies were identified as having an overall high risk of bias (Fig. 2). Among these studies, the most frequently observed domain with a high risk of bias was the "deviation from intended interventions," followed by "measurement of outcome," and subsequently, "selection of reported results." A comprehensive summary of the risk of bias assessment for all 17 studies is presented in Supplementary Table 1.

Findings form the quantitative analysis

Normalization included mapping scores from different pain scales (VRS, NRS, and Heft Parker) onto a common scale for unified comparison with the VAS. This facilitated a comprehensive synthesis of diverse pain assessment metrics.

Subgroup meta-analyses assessed the efficacy of combined intraoral laser therapy relative to control groups (conventional treatment and placebo) over several time periods (Fig. 3). While laser therapy was marginally more effective than conventional treatment at 8 h (Fig. 3b), 24–30 h (Fig. 3d), and 48–72 h (Fig. 3e), these differences were not statistically significant. However, laser therapy significantly outperformed placebo consistently up to 48 h. For instance, there were significant statistical differences at several time intervals: at 4 to 6 h, the odds ratio (OR) was 11.1 (95% CI: 2.69–45.6) with $p<0.001$; at 8 h, the OR was 12.9 (95% CI: 252.1-660003) with $p<0.001$; at 12 h, the OR was 11.2 (95% CI: 2.51–49.9) with $p=0.002$; and at 24 h, the OR was 15.9 (95% CI: 1.34–190.6) with $p=0.029$. Particularly, when comparing combined controls, laser therapy demonstrated a significant advantage from 4 to 72 h.

LLLT was evaluated solely against placebos, without comparison to conventional treatments. The analysis differentiated effects in initial RCT, re-RCT, and combined scenarios across several intervals (Fig. 4). Although results were not statistically significant at any time point, combined data showed a marginal preference for LLLT at 4–6 h (OR = 1.92 [95%CI: 0.29–12.9]; $p=0.501$) and 8 h (OR = 1.29 [95%CI: 0.34-5.00]; $p=0.702$). Conversely, LLLT was slightly less favorable at 48–72 h (OR = 0.73 [95%CI: 0.16–3.22]; $p=0.672$), particularly in the re-RCT scenario (OR = 0.64 [95%CI: 0.11–3.71]; $p=0.618$).

Figure 5 illustrates a meta-analysis comparing PDT to conventional treatment and placebo over three time-intervals: 24–30 h, 48–72 h, and 7 days. PDT showed a marginally better outcome than conventional treatment at 24–30 h (Fig. 5a; $p=0.597$) and placebo at the same interval (Fig. 5b; $p=0.143$), though these differences were not statistically significant.

In the subgroup meta-analyses assessing laser disinfection post-operativepain, only placebos served as controls due to the absence of conventionaltreatments in the available literature. Initial RCTs and re-RCTs were analyzedboth separately and together (Fig. 6). Laser disinfection showed a significantbeneficial effect in most RCT intervals, except at 7 days. In contrast, lasers inre-RCT studies had neutral effects. Remarkably, the earliest time interval (i.e.,12 hrs) included only RCTs, showing a substantial benefit from lasers (Fig. 6a;OR = 11.2 [95%CI: 2.51-49.9]; $p=0.001$). However, the latest time interval (i.e., 7days) did not demonstrate significant differences (Fig. 6d; OR = 4.48 [95%CI:0.66-30.3]; $p=0.124$). For combined RCT and re-RCT results, significantadvantages of laser disinfection over placebo were observed at 24-30 h Fig. 6b; OR = 11.0 [95%CI: 2.56-47.9]; $p=0.001$) and 48-72 h Fig. 6c;OR = 6.69 [95%CI: 1.27-35.5]; $p=0.025$).

In the subgroup analysis for irrigation activation using Er: YAG, data were available for only two time-intervals: one study at 24–30 h and another at 48–72 h, both comparing the laser to conventional treatments as the control group (Fig. 7). The first interval showed no significant differences ($p=0.314$), whereas the second interval demonstrated significant improvements with the laser ($p<0.001$).

Meta-regression analyses compared the efficacy of combined laser treatments at the 24–30-h interval against conventional treatments and placebo (Suppl. Fig. S1a), as well as against these combined controls (Suppl. Fig. S1b). The first meta-regression revealed that lasers significantly reduced pain compared to placebo, showing a 32.4% higher rate of 'no/mild pain' in the laser group ($p=0.036$). No significant differences were observed

Treatment type	Study	Laser group	Control group	Sample	Arch type	Tooth type Laser group	Tooth type Control group	Age (Mean / Range)	Instrument to document post-op pain	Anesthetic solution	Medication	Number of visits	Method of instrumentation	Working length / limit of instrumentation	Irrigants used	Obturation used in both groups	Occurrence of Sealer/ obturation material extrusion	Operator experience
RCT	**Alves-Silva (2022)**	PDT	Without laser irradiation (Placebo) Ultrasonic activation	60	*Laser Group* Maxilla: 28 Mandible: 2 *Control Group* Maxilla: 30 Mandible: 0	Incisor: 21 Canine: 2 Premolar: 7	Incisor: 21 Canine: 3 Premolar: 6	Laser Group: 34 Control Group: 34	VAS	Lidocaine	No medication used	Single	Reciprocating motion using RECIPROC files sizes #25 and #40	NR (Used apex locator)	2% CHX 17% EDTA Sterile saline	Single Reciproc gutta-percha cone with Endomethasone N cement	NR	Operator: One Qualification: NR
RCT	**Coelho (2019)**	PDT	Ultrasonic activation	60	*Laser Group* Maxilla: 19 Mandible: 11 *Control Group* Maxilla: 20 Mandible: 9	Incisors: 20 Canine: 1 Premolar: 9	Incision: 17 Canine: 5 Premolar: 8	Laser Group: 47 Control Group: 47	VAS	Articaine	Ibuprofen 600 mg *Laser Group* 0.13 tablets *Control Group* 0.77 tablets	Single	Reciprocating motion using RECIPROC	1 mm short of the radiographic apex (Used apex locator)	2.5% NaOCl 17% EDTA	Warm vertical condensation using gutta-percha and AH plus sealer	NR	NR
RCT	Vilas-boas (2021)	PDT	Ultrasonic activation	65	Laser Group: Maxilla: 14 Mandible: 19 *Control Group* Maxilla: 16 Mandible: 16	Premolar: 8 Molar: 25	Premolar: 13 Molar: 19	Laser Group: 45 Control Group: 48	VAS	Lidocaine	Ibuprofen 600 mg *Laser Group* 0.24 tablets *Control Group* 0.97 tablets	Two visits	Rotary motion using ProTaper	1 mm short from the 0.0 reading of the electronic apex locator	2.5% NaOCl 17% EDTA Sterile saline	NR	NR	NR
RCT	Lopes (2018)	LLLT	Without laser irradiation (Placebo)	60	*Laser Group* Mandible: 30 *Control Group* Mandible: 30	Molars: 30	Molars: 30	Laser Group: 30 Control Group: 28	NRS/VRS	Lidocaine	Ibuprofen 600 mg *Laser Group* $n=2$ (6.6%) *Control Group* $n=2$ (6.6%)	NR	Reciprocating motion using WaveOne	NR (Used apex locator)	2.5% NaOCl 17% EDTA	Thermomechanical compaction using gutta-percha and AH plus sealer	Laser Group: $n=10$ (33.3%) Control Group: $n=13$ (43.3%)	Operator: One Qualification: NR
RCT	Nabi (2018)	LLLT	Without laser irradiation (Placebo)	60	NR	NR	NR	Laser Group: 35 Control Group: 35	Heft parker pain survey	Articaine	No medication used	Single	Rotary motion using ProTaper	0.5 mm short of the radiographic apex (Used apex locator)	5.25% NaOCl	Lateral compaction using gutta-percha and AH plus sealer	NR	NR
RCT	Naseri (2020)	LLLT	Without laser irradiation (Placebo)	75	*Laser Group* Maxilla: 20 Mandible: 30 *Control Group* Maxilla: 7 Mandible: 18	Molars: 50	Molars: 25	Laser Group: 18 to 60 Control Group: 18 to 60	VAS/NRS	Lidocaine	Ibuprofen 400 mg *Laser Group* 0.8 ± 0.64 tablets *Control Group* 2.16 ± 1.625 tablets	Single	Rotary motion using ProTaper	NR	2.5% NaOCl	Cold lateral compaction using gutta-percha and AH26 sealer	NR	NR
RCT	Yıldız (2018)	LLLT	Without laser irradiation (Placebo)	28	*Laser Group* Mandible: 14 *Control Group* Mandible: 14	Molars: 14	Molars: 14	Laser Group: 28 Control Group: 26	VAS	Articaine	Ibuprofen 400 mg *Laser Group* $n=1$ (7.1%) *Control Group* $n=3$ (21.4%)	Single	Reciprocating motion using RECIPROC	NR (Used apex locator)	1% NaOCl 5% EDTA	Matched single cones with 2Seal sealer	NR	Operator: One Qualification: Endodontic Specialist

Continued

Treatment type	Study	Laser group	Control group	Sample	Arch type	Tooth type Laser group	Tooth type Control group	Age (Mean / Range)	Instrument to document post-op pain	Anesthetic solution	Medication	Number of visits	Method of instrumentation	Working length / limit of instrumentation	Irrigants used	Obturation used in both groups	Occurrence of Sealer/ obturation material extrusion	Operator experience
RCT	Erkan (2022)	Irrigation activation with Er: YAG	Manual dynamic activation Sonic system with EDDY Ultrasonic activation	200	*Laser Group* Mandible: 80 *Control Group* Mandible: 120	Premolar: 80	Premolar: 120	Laser Group: 33 Control Group: 33	VAS	Articaine	No medication used	Single	Rotary motion using ProTaper	NR (Used apex locator)	3% NaOCl 17% EDTA Sterile saline	Cold lateral compaction using gutta-percha and AH plus sealer	NR	Operator: One Qualification: Endodontic Specialist
RCT	Liapis (2021)	Irrigation activation with ER: YAG	Ultrasonic activation	55	NR	Non-molar: 13 Molars: 15	Non-molar: 13 Molars: 15	Laser Group: 44 Control Group: 41	VAS	Articaine	Ibuprofen 400 mg *Laser Group* 6 h ($n=2$) (7.7%) 24 h ($n=1$) (3.9%) 48 h ($n=1$) (3.9%) 72 h ($n=1$) (3.9%) *Control Group* 6 h ($n=7$) (26.0%) 24 h ($n=5$) (18.5%) 48 h ($n=2$) (7.4%) 72 h ($n=1$) (3.7%)	Single	Rotary motion using ProTaper	NR (Used apex locator)	3% NaOCl 17% EDTA	Continuous wave of compaction using gutta-percha and AH plus sealer	NR	Operator: One Qualification: NR

Continued

Treatment type	Study	Laser group	Control group	Sample	Arch type	Tooth type Laser group	Tooth type Control group	Age (Mean / Range)	Instrument to document post-op pain	Anesthetic solution	Medication	Number of visits	Method of instrumentation	Working length / limit of instrumentation	Irrigants used	Obturation used in both groups	Occurrence of Sealer/ obturation material extrusion	Operator experience
RCT	Kaplan (2021)	Disinfection with Diode	Without laser irradiation (Placebo)	60	NR	Single rooted teeth: 30	Single rooted teeth: 30	Laser Group: 34 Control Group: 32	VAS	Articaine	Ibuprofen 600 mg *Laser Group* No medication used *Control Group* 8 h ($n=12$) (40%) 24 h ($n=7$) (23.3%) 48 h ($n=4$) (13.3%)	Two visits	Rotary motion using ProTaper	NR (Used apex locator)	2.5% NaOCl 17% EDTA Sterile saline	Cold lateral compaction using gutta-percha and AH plus sealer	NR	Operator: One Qualification: NR
RCT	Morsy (2018)	Disinfection with Diode	Without laser irradiation (Placebo)	56	*Laser Group* Maxilla: 28 *Control Group* Maxilla: 28	Anterior: 28	Anterior: 28	Laser Group: 25 Control Group: 28	NRS	Articaine	No medication used	Two visits	Rotary motion using ProTaper	NR (Used apex locator)	2.5% NaOCl 17% EDTA Sterile saline	Modified single cone technique using gutta-percha and ADSEAL resin-based root canal sealer	NR	Operator: One Qualification: Endodontic Specialist
RCT	Koba (1999)	Disinfection with Nd: YAG	Without laser irradiation (Placebo)	44	NR	Incisors: 12 Premolars: 5 Molars: 5	Incisors: 12 Premolars: 5 Molars: 5	Laser Group: 26 to 59 Control Group: 26 to 59	Pain upon percussion	NR	No medication used	Single	Stepback technique using manual K-files	1 mm short of the radiographic apex (Used apex locator)	5% NaOCl 3% H_2O_2	Laterally condensed gutta-percha and Canals N sealer	NR	NR
RCT	Tunc (2021)	Disinfection with Nd: YAG and Diode	Without laser irradiation (Placebo)	102	*Laser Group* Maxilla: 36 Mandible = 32 *Control Group* Maxilla: 17 Mandible = 17	Single rooted teeth: 68	Single rooted teeth: 34	Laser Group: 34 Control Group: 34	VAS	Articaine	No medication used	Single	Rotary motion using Revo-S	NR (Used apex locator)	2.5% NaOCl 17% EDTA Sterile saline	Lateral condensation using gutta-percha and epoxy resin-based sealer	No radiographic extrusion was observed in any case.	Operator: One Qualification: NR
re-RCT	Arslan (2017)	LLLT	Without laser irradiation (Placebo)	36	*Laser Group* Mandible: 18 *Control Group* Mandible: 18	Molars: 18	Molars: 18	Laser Group: 33 Control Group: 26	VAS	Articaine	Drug: NR *Laser Group* $n=1$ (5.5%) *Control Group* $n=9$ (50%)	Two visits	Reciprocating motion using RECIPROC	NR (Used apex locator)	1% NaOCl 2% Citric acid Sterile Saline	Lateral compaction using gutta-percha and Sealapex sealer	NR	Operator: Two, one for each group Qualification: NR

Continued

Treatment type	Study	Laser group	Control group	Sample	Arch type	Tooth type Laser group	Tooth type Control group	Age (Mean / Range)	Instrument to document post-op pain	Anesthetic solution	Medication	Number of visits	Method of instrumentation	Working length / limit of instrumentation	Irrigants used	Obturation used in both groups	Occurrence of Sealer/ obturation material extrusion	Operator experience
re-RCT	Asnaashari (2017)	LLLT	Without laser irradiation (Placebo)	61	*Laser Group* Maxilla: 20 Mandible: 21 *Control Group* Maxilla: 10 Mandible: 10	Molars: 41	Molars: 20	NR	VAS	Articaine	Drug: NR *Laser Group* *n*=4 (6.6%) *Control Group* *n*=4 (6.6%)	Single	NR	NR	NR	NR	NR	NR
re-RCT	Fazlyab (2021)	LLLT	Without laser irradiation (Placebo)	36	*Laser Group* Mandible: 18 *Control Group* Mandible: 18	Molars: 18	Molars: 18	Laser Group: 44 Control Group: 44	VAS	Articaine	No medication used	Single	Dis-obturation using D RaCe retreatment system followed by instrumentation with RaCe rotary instruments if needed.	0.5 mm short from the 0.0 reading of the electronic apex locator	5.25% NaOCl 17% EDTA Sterile Saline	Lateral compaction using gutta-percha and AH plus sealer	NR	Operator: One Qualification: NR
re-RCT	Genc Sen (2019)	Disinfection with Diode	Without laser irradiation (Placebo)	84	NR	Single rooted teeth: 42	Single rooted teeth: 42	Laser Group: 31 Control Group: 36	NRS	Articaine	Ibuprofen 400 mg *Laser Group* 0.11 ± 0.52 tablets *Control Group* 1.11 ± 2.14 tablets	Single	Dis-obturation using ProTaper Universal Retreatment files followed by instrumentation with manual K-files if needed.	NR (Used apex locator)	2% NaOCl 17% EDTA	Cold lateral condensation using gutta-percha and epoxy resin-based sealer	NR	Operator: One Qualification: NR

Table 3. Summary of key characteristics of included studies. RCT, root canal therapy; re-RCT, retreatment of RCT; PDT, photodynamic therapy; LLLT, low-level laser therapy; PBM, photobiomoodulation; Er: YAG, Erbium-doped Yttrium Aluminium Garnet; nd: YAG, neodymium-doped Yttrium Aluminum Garnet; VAS, visual analog scale; VRS, verbal rating scale; NRS, numerical rating scale; CHX, chlorhexidine; EDTA, ethylenediaminetetraacetic acid; NaOCl, sodium hypochlorite; NR, not reported

Study ID (first author, year)	Laser wavelength	Laser activation protocol
Alves-Silva (2022)	660 nm	The treatment involved activating 3 mL of 0.005% methylene blue with a 660 nm red gallium aluminum arsenide diode laser at 100 mW for 90 s after a 3-min pre-irradiation period. The application consisted of a 15-sec static exposure at the canal apex, then helical movements toward the crown, delivering a total of 9 J and an energy density of 320 J/cm².
Coelho (2019)	660 nm	The laser tip, covered in aluminum foil, employed a size 25, 0.04 taper optical fiber, which was positioned to the working length. The laser settings were 660 nm and 100 mW, delivering 18 J of energy and an energy density of 600 J/cm² over a 3 min duration, with the tip being moved gently in a vertical direction.
Erkan (2022)	2940 nm	For the PIPS group, an Er: YAG laser with a 600 µm, 9 mm long PIPS tip was set to a 2,940 nm wavelength, delivering 20 mJ per pulse at 15 Hz and 0.3 W, with a 50 µs pulse frequency. The tip was held stationary in the access cavity while activating a 3% NaOCl solution in three 20-sec intervals, followed by the same activation sequence for 2 ml of 17% EDTA solution. The SWEEPS procedure utilized an Er: YAG laser source (2,940 nm) with the SWEEPS fiber tip in ultra-short dual pulse mode (25 µs, Auto SWEEPS mode). Set at 20 mJ per pulse, 15 Hz, and 0.3 W power with a 50 µs pulse frequency, the tip was held steady in the access cavity. Activation followed the same protocol and used identical irrigation solutions as in the PIPS group.
Kaplan (2021)	980 nm	The laser was programmed to pulsed mode, outputting 2.4 W with 12 J delivered per cycle at a 20 µs pulse duration. The treatment protocol was 10 s of irradiation followed by a 10-sec rest, comprising one cycle, and repeated four times per canal. The average power was 1.2 W, with a power density of 3822 W/cm² at 50 Hz frequency, using a 25 mm fiber optic tip positioned at the working length.
Koba (1999)	1064 nm	Using a 320 µm flexible optical fiber, the laser was set to a power of 1 W and a frequency of 15 pulses per second, with 66 mJ per pulse and a pulse duration of 150 picoseconds for a duration of 1 s. The fiber tip was placed in contact with the root canal's apical seat during laser activation.
Liapis (2021)	2940 nm	Using a dental handpiece (H14, Fotona) paired with a 400 µm PIPS tip and both water and air off, the laser was set to 20 mJ pulse energy, 15 Hz frequency, and 50 µs pulse length. The tip was positioned above the canal entrance, and each canal received two 30-sec activation cycles with a 2 mL 3% NaOCl rinse in between. Throughout, the pulp chamber was kept filled with 3% NaOCl.
Lopes (2018)	808 nm	The laser was applied perpendicularly to the gum, at four points per tooth—two buccal, two lingual, aligned with the root apices of mandibular molars. It was set at 0.10 W, delivering 2.5 J per point over 25 Sect. (100 s total per tooth), with an energy density of 90 J/cm² per point, totaling 360 J/cm² per tooth.
Morsy (2018)	980 nm	A 200 µm optical fiber laser (Lite medics, Italy) set to 1.2 W in pulsed mode was employed. The protocol involved 5 s of irradiation followed by a 10 s pause, constituting one cycle, repeated four times per tooth. The fiber tip was positioned 1 mm from the apex, then activated and drawn coronally at approximately 2 mm/s in a helical pattern to irradiate the canal walls.
Nabi (2018)	905 nm 875 nm	The laser tip was applied perpendicularly in contact mode to the periapical regions buccally and lingually. The duration was 3 min, with powers set to 12–16 mW for 875 nm broadband infrared (IR) irradiation at 60 mW, and 640 nm for visible red irradiation at 7 mW.
Naseri (2020)	808 nm	The BI group was subjected to 80 s of laser irradiation on the buccal surface, while the BLI group received 80 s each on both buccal and lingual surfaces. A 100-mW laser with a 600 µm fiber diameter was utilized for the procedure.
Tunc (2021)	1064 nm 940 nm	The Nd: YAG laser used a 200 µm fiber at 1 W output, with an energy density of 100 mJ/s and a 15 Hz frequency. The fiber tip was inserted into the root canal to 1 mm shy of the working length and retracted in a spiral motion with the laser active for 5 s. This step was repeated four times with a 20 s rest between each. The laser output was set to 1 W in CW mode with an energy density of 100 mJ/pulse at 15 Hz. A 200 µm Biolase optical fiber reached the working length, irradiating the root canal from the apex to the coronal end at 2 mm/s in a circular motion for complete canal wall contact. This was repeated four times with 20-sec intervals.
Vilas-boas (2021)	660 nm	In the PG group, the canals were treated with 150 µM Methylene Blue (MB), left in place for 2 min. A Laser Duo (MMOptics, São Carlos, Brazil) delivering 100 mW and 600 J/cm² was then applied for 3 min in each canal, imparting a total of 18 J of energy. The laser was administered via an optical fiber sized 25.04, positioned up to the working length (WL).
Yıldız (2018)	970 nm	A 200-µm optical fiber with a bleaching tip was positioned 10 mm from the periapical tissue, activated at 0.5 W and 10 Hz with a power density of ~ 286 W/cm². The periapical tissues of the mesial and distal root apices were irradiated for 30 s each.
Arslan (2017)	970 nm	The mesial and distal root apices were each irradiated for 30 s at 0.5 W and 10 Hz, yielding a power density of ~ 2.86 W/cm². A 200-µm optical fiber with a bleaching tip was utilized, positioned roughly 10 mm from the tissue for the application.
Asnaashari (2017)	808 nm	Laser treatment was administered using a single dose at an 808 nm wavelength with a power setting of 100 mW, utilizing a 600 µm fiber, delivering a dose of 70 J/cm² over a duration of 80 s.
Fazlyab (2021)	980 nm	The laser was calibrated to an energy density of 6.89 W/cm² and power of 0.5 W, using a 10 mm diameter tip for 15 s. It was directed at the soft tissue overlying the mesial and distal tooth apices from the buccal aspect, with the laser handpiece tip maintained around 10 mm away from the mucosa.
Genc Sen (2019)	940 nm	Laser energy was delivered via a 200-µm fiber tip at 1 W in continuous mode. The tip was placed at the working length and the canals were irradiated at a speed of 2 mm/s, employing circling movements from apical to coronal parts. This process was repeated four times per canal with 20-sec intervals between applications.

Table 4. Laser wavelength and activation protocols of included studies.

between laser and conventional methods ($p = 0.172$) or between conventional and placebo methods ($p = 0.658$). The second meta-regression also indicated significant improvements with lasers, with a 28.9% increase in 'no/mild pain' rates compared to combined controls ($p = 0.026$). Additionally, a meta-regression analysis s conducted to assess the impact of various independent factors, including mean age, gender distribution (percentage of males), anesthetic solution, tooth position diversity (percentage of different positions), and treatment type. Among these factors, only tooth position showed a statistically significant influence, indicating that upper maxillary teeth achieved superior outcomes when treated with laser modalities ($p = 0.079$).

Discussion

Postoperative pain following endodontic procedures is a significant concern for both patients and oral health providers[40]. The incidence of acute pain after RCT can vary widely, ranging from 1–65%[41]. This wide range can be attributed to the multifactorial nature of pain[41]. The primary cause of postoperative pain after RCT in ETT is the inflammatory response triggered by injury to the periapical tissues[42,43]. Such injury can result from mechanical, chemical, and microbial factors[42,43]. Endodontic interventions, through the disruption of periapical tissues, may induce therelease inflammatory mediators into the periapical tissues, including prostaglandins, leukotrienes, bradykinin, platelet-activating factor, and substance P, all of which can directly stimulate or

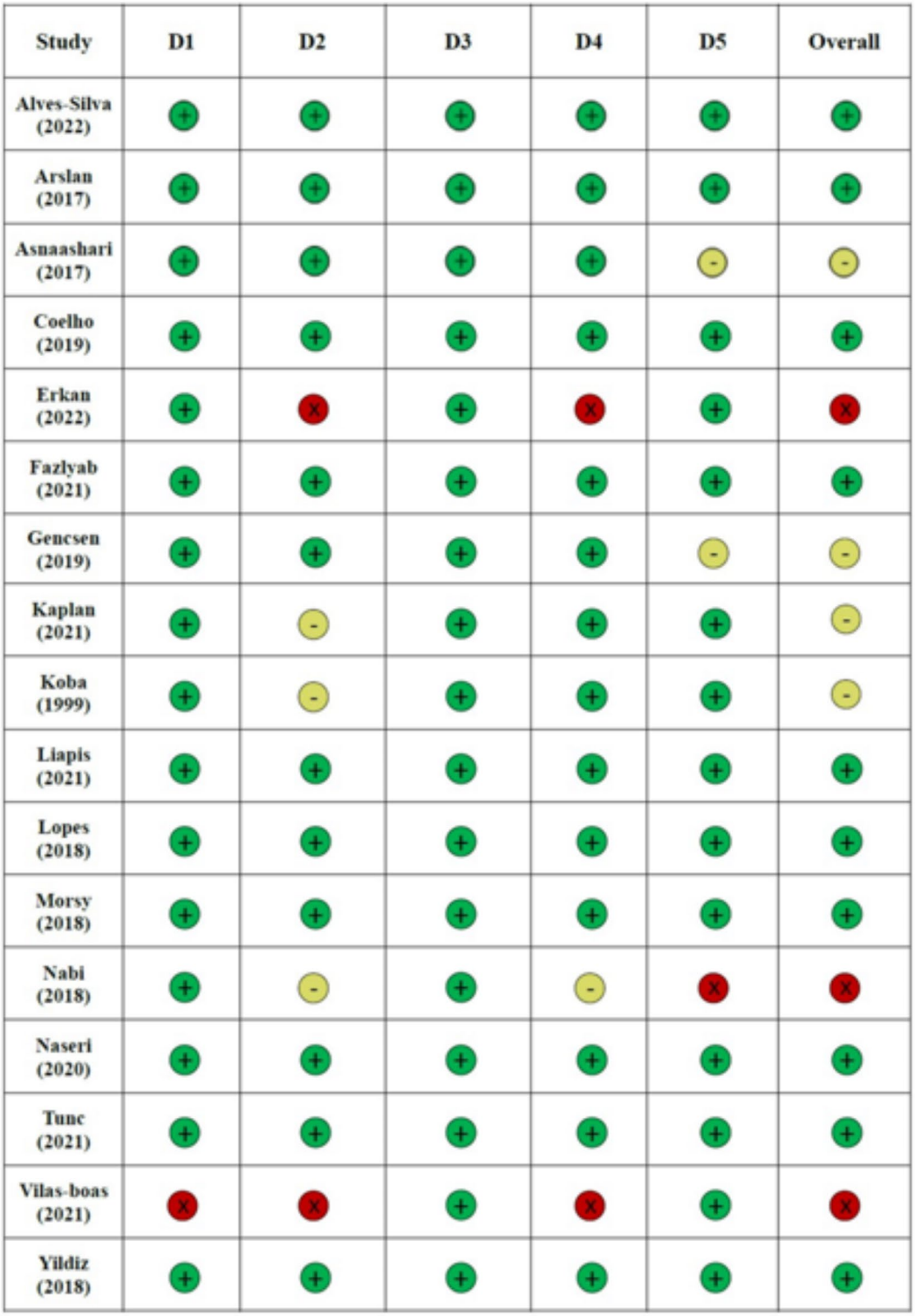

Fig. 2. Risk of bias assessment via Cochrane's collaboration tool RoB 2. *Domains*: D1, Randomization process; D2, Deviations from intended intervention; D3, Missing outcome data; D4, Measurement of the outcome; D5, Selection of the reported result. *Assessors' judgement*: ×, High; -, Some concerns; +, Low.

sensitize nociceptors, leading to pain[44–46]. To enhance patient comfort and the overall success of RCTs, general dental practitioners and endodontists utilize various measures to minimize these contributing factors. These measures include the use of appropriate techniques, medications, and materials, as well as patient education and communication, which are essential for managing expectations and addressing any concerns related to post-treatment pain[40,44]. Thus, the present systematic review and meta-analysis represent an effort in evaluating

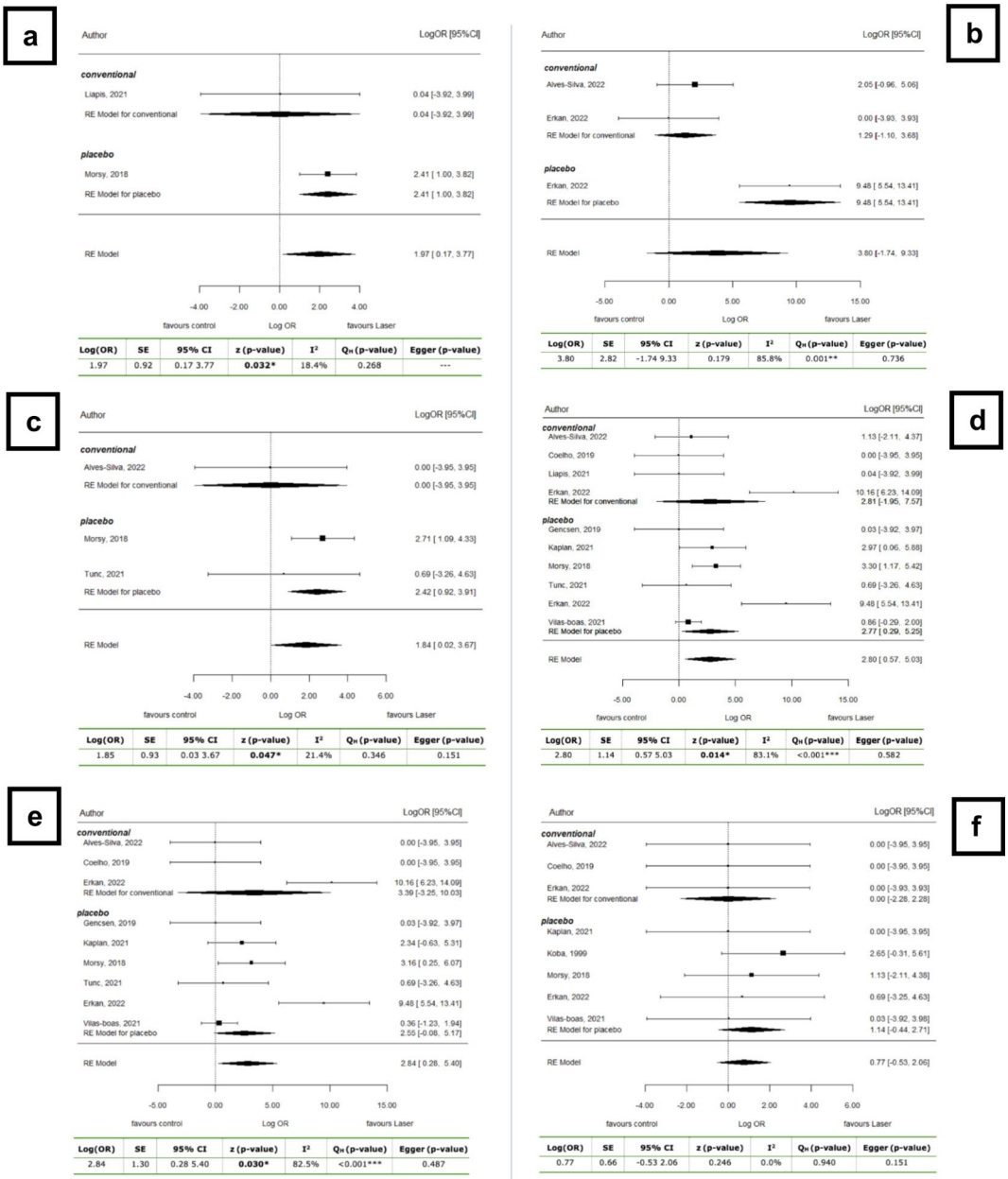

Fig. 3. Subgroup meta-analysis comparing intraoral laser therapy to conventional treatment and placebo at intervals: (**a**) 4–6 h, (**b**) 8 h, (**c**) 12 h, (**d**) 24–30 h, (**e**) 48–72 h, and (**f**) 7 days.

the effectiveness of laser treatment modalities in reducing postoperative pain after both primary and secondary endodontic treatments compared to conventional methods.

The literature on laser treatments in endodontics has various limitations. Meire et al.[31] evaluated several adjunctive treatment modalities, such as ozone therapy and UAI, without exclusively focusing on laser treatments. Guerreiro et al. (2021)[29] included studies on LLLT but did not compare different laser treatment methods. Elafifi-Ebeid et al. (2023)[28] limited their analysis to RCT studies, excluding re-RCT, and focused solely on intracanal laser irradiation, overlooking LLLT and PBM. Chen et al. (2019)[30] emphasized LLLT exclusively, neglecting other laser therapies. Lastly, Alonaizana & AlFawaz (2019)[32] appraised the impact of PDT on postoperative endodontic pain management but faced limitations, including a scarcity of studies and a qualitative analysis approach, with many clinical studies lacking specific control or comparison groups.

Laser applications in reducing postoperative pain in endodontics consist of various techniques. These techniques range from external laser application to the apices of affected teeth, as seen in PBM or LLLT[47,48], to disinfecting the canals through the activation of a photosensitizer using a laser with a specific wavelength, as in the case of PDT[49,50], or simply disinfecting the radicular canal or activating irrigation solution using a direct laser source like Er: YAG (Fig. 7) or Diode lasers[21,51]. Our meta-analyses suggest that various laser treatments may have advantages in reducing postoperative pain compared to conventional techniques. These

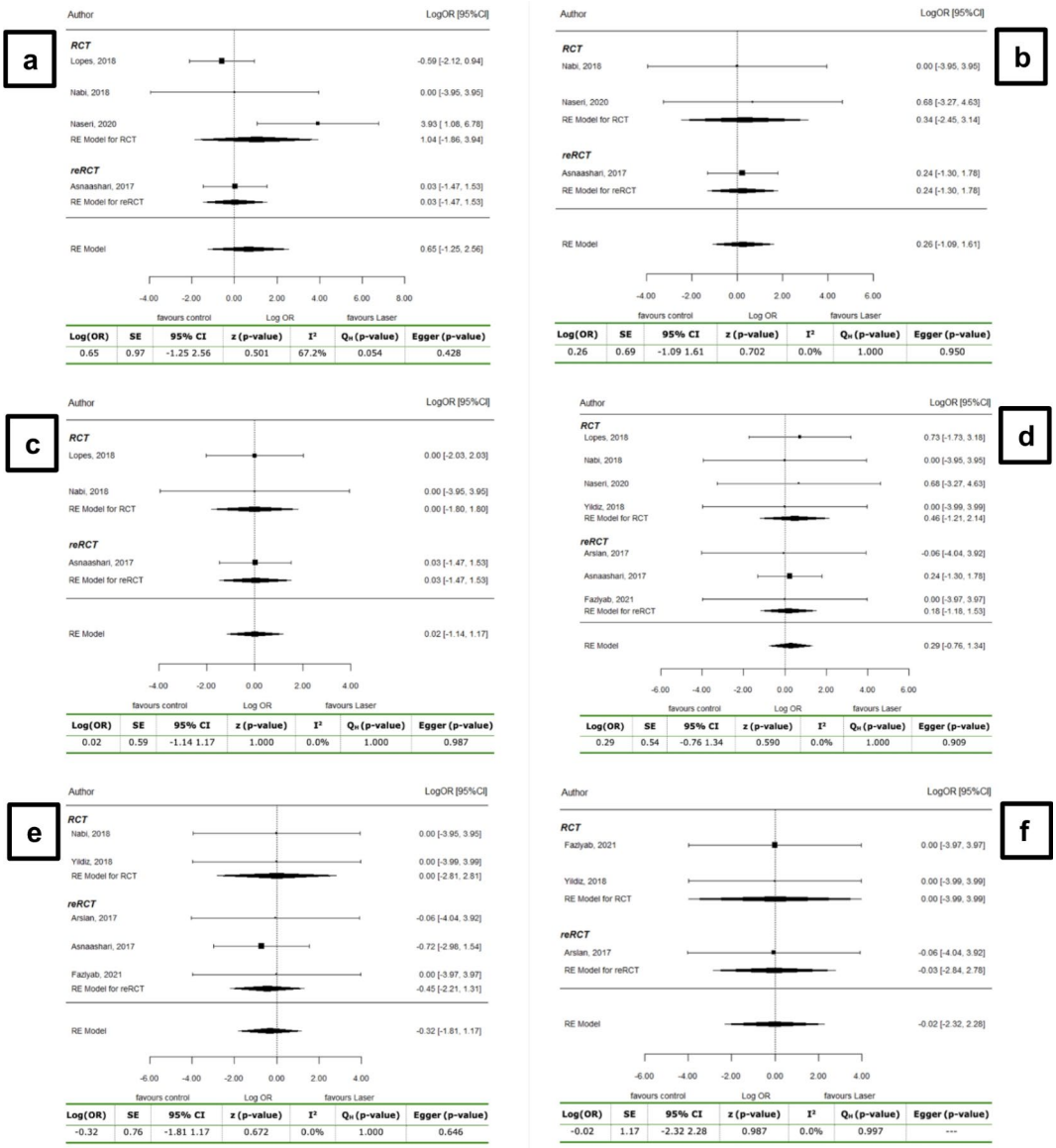

Fig. 4. Subgroup meta-analysis of low-level laser therapy versus placebo for managing postoperative pain analyzing initial root canal treatment and retreatment scenarios across intervals: (**a**) 4–6 h, (**b**) 8 h, (**c**) 12 h, (**d**) 24–30 h, (**e**) 48–72 h, and (**f**) 7 days. *Note*: The 4 to 5-day interval has been excluded from the diagram due to insignificance and space constraint.

methods show potential benefits, particularly in the early postoperative intervals, and often outperform placebo treatments. However, the current evidence has some limitations, and further studies are needed to confirm these findings[51–62]. PBM, in particular, is a therapeutic technique involving the application of low levels of red and near-infrared light to stimulate cellular processes[47,48]. PBM functions by reducing the production of inflammatory prostaglandins, interleukin 1β, and TNF-alpha[63,64], which are known to contribute to the inflammatory processes often associated with pain. In the current meta-analysis, PBM significantly reduced postoperative pain following endodontic procedures when compared to conventional techniques. Notably, PBM was the most frequently employed laser treatment modality, with 7 studies utilizing this technique[23,53,55,51,60,61,65] This prevalence suggests the ease of use, safety, and the non-toxic, non-allergenic nature of PBM treatment.

PDT is a medical treatment that involves the use of a photosensitizer, a light-sensitive compound placed inside the radicular canal, typically in the form of a gel or liquid[49,50]. Once applied, a specific wavelength of light is directed onto the treated area, activating the photosensitizer. This activation process leads to the generation of singlet oxygen and other reactive oxygen species (ROS)[66,67], highly reactive compounds that can damage and effectively kill bacterial cells[66,67]. Furthermore, PDT has been found to influence the permeability of the cell membrane to ions such as calcium (Ca2+), sodium (Na+), and potassium (K+). These alterations can impact various cellular processes, including signal transduction and membrane potential[26,27], leading to the enhanced degradation of the bradykinin peptide, a contributor to inflammation reduction, particularly pain

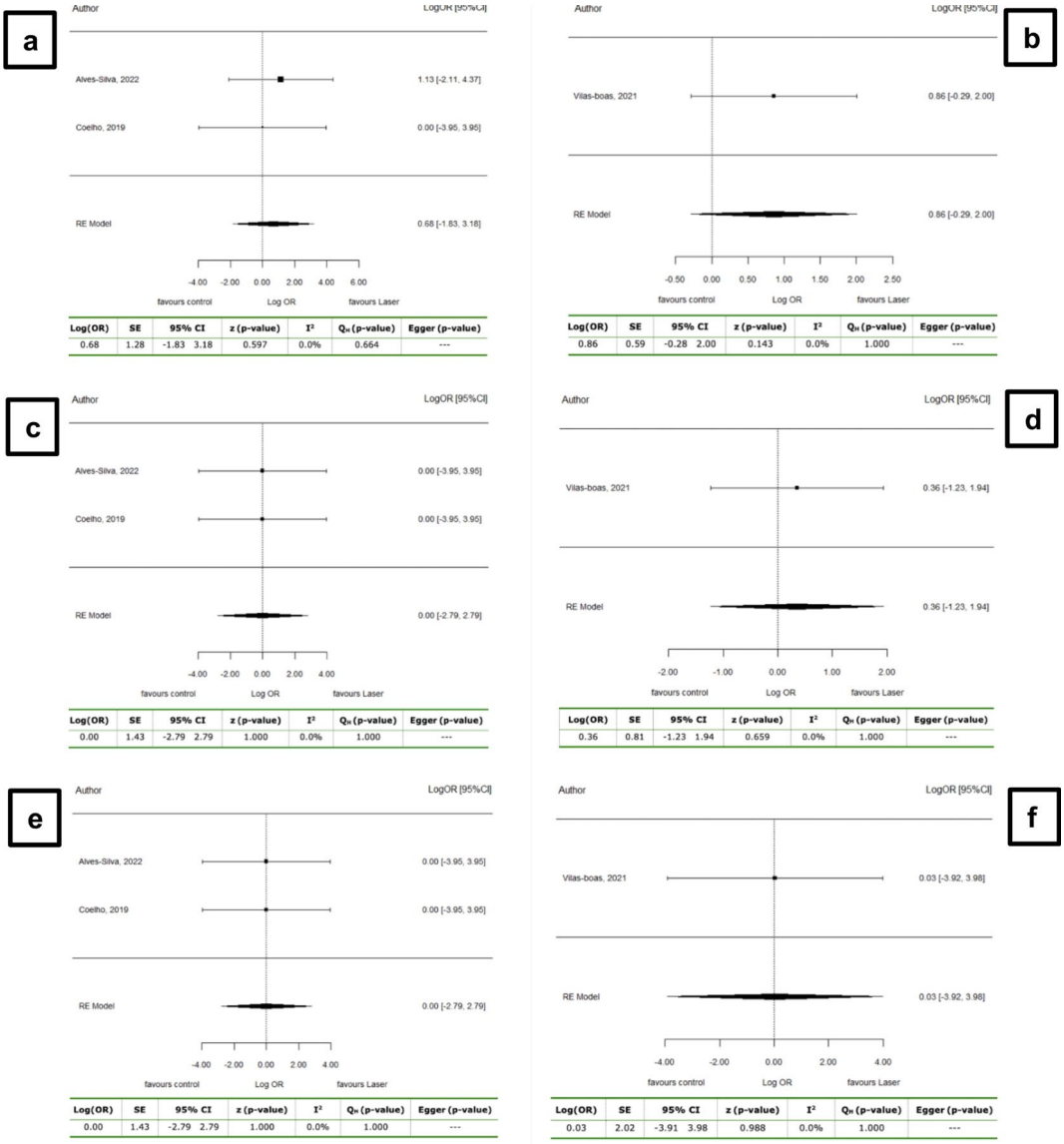

Fig. 5. Subgroup meta-analysis of photodynamic therapy compared with placebo andconventional treatments for postoperative pain management at specific intervals: (**a**) 24-30 hrs with conventional treatment, (**b**) 24-30 hrs with placebo, (**c**) 48-72 hrs withconventional treatment, (**d**) 48-72 hrs with placebo, (**e**) 7 days with conventionaltreatment, and (**f**) 7 days with placebo.

reduction[26,27]. Additionally, changes in permeability can boost the activity of cellular receptors, potentially triggering the production of natural pain-relieving endorphins[26,27]. The findings from the present secondary study demonstrated the effectiveness of PDT in reducing postoperative pain following endodontic procedures. These results are consistent with a prior review by Alonaizana & AlFawaz (2019)[32], which examined the impact of PDT on postoperative endodontic pain management. However, it is important to note that the previous review had limitations, including a limited literature search involving only 30 studies. Additionally, the review by Alonaizana & AlFawaz (2019)[32] includes various types of clinical studies without specific control or comparison groups to assess the effect of PDT. Moreover, no statistical analysis was performed to determine the true impact of the qualitative data collected.

Our meta-analysis findings indicate that while intracanal laser therapy does not show a significant improvement over conventional treatments, it consistently outperforms placebo and demonstrates notable benefits when combined with controls, particularly in the short-term postoperative period (4 to 72 h). Subgroup analyses reveal that LLLT shows a slight, albeit non-significant, preference for pain reduction at 4–6 and 8 h post-treatment. However, its effectiveness diminishes over longer periods, especially in re-RCTs. These findings are corroborated by meta-regression analyses at 24–30 h, where laser treatments significantly improved 'no/mild pain' outcomes compared to placebo and combined controls (Suppl. Fig. S1a). This aligns with previous studies suggesting that LLLT can provide short-term pain relief, likely due to its anti-inflammatory effects and the promotion of cellular repair mechanisms[68,69].

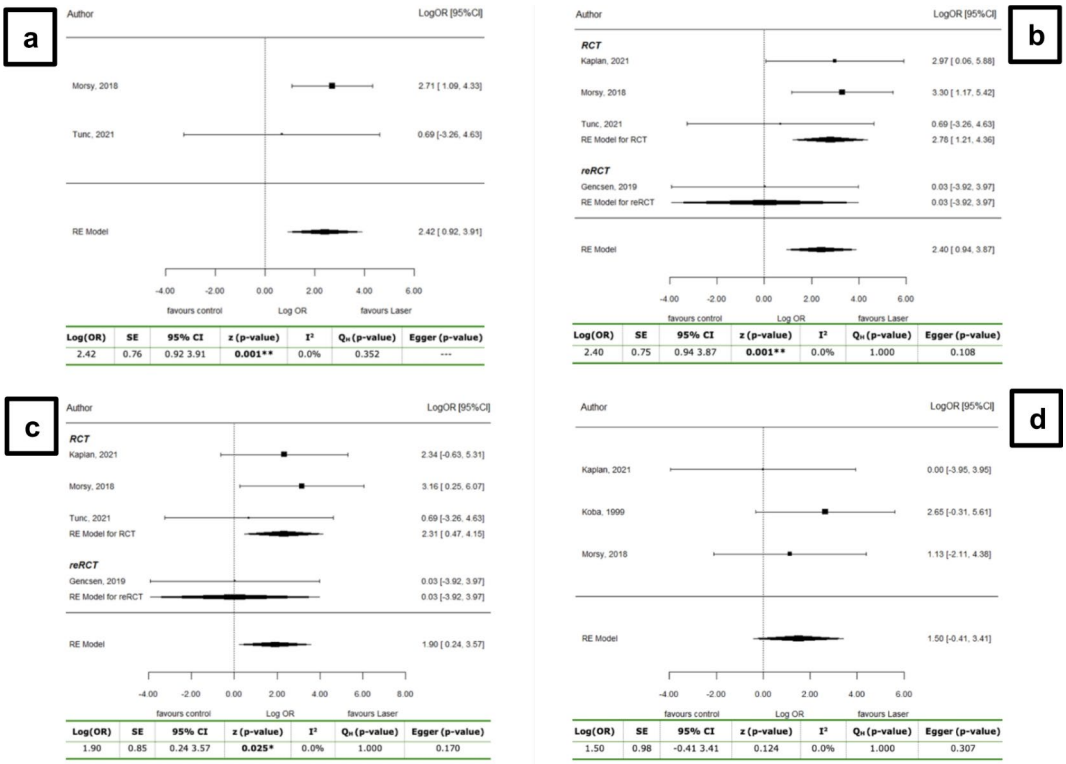

Fig. 6. Subgroup meta-analysis of disinfection versus placebo for postoperative pain in root canal treatment (RCT) and retreatment (re-RCT) scenarios across various intervals: (**a**) placebo at 12 h in RCT, (**b**) placebo at 24–30 h in RCT, (**c**) placebo at 24–30 h in both RCT and re-RCT, and (**d**) placebo at 7 days in RCT.

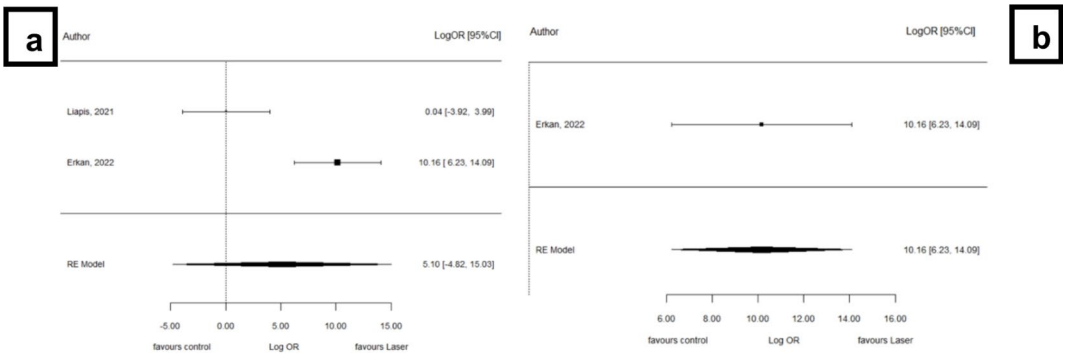

Fig. 7. Subgroup analysis for irrigation activation using Er: YAG versus conventional for postoperative pain in root canal treatment scenarios across various intervals: (**a**) At 24–30 h and (**b**) At 48–72 h.

Our analysis indicates that PDT marginally outperforms conventional treatment and placebo at 24–30 h, though the results were not statistically significant (Fig. 5). The mechanism of PDT involves the activation of photosensitizers by light, producing reactive oxygen species that can reduce bacterial load and inflammation[70]. While these biological effects suggest a potential for pain reduction, our data suggests that the clinical benefits of PDT for postoperative pain management in endodontics are limited and require further investigation. Laser disinfection showed significant pain reduction shortly after treatment in root canal therapies, particularly in the early postoperative intervals. However, there were no significant benefits in retreatment scenarios or over extended periods, such as seven days (Fig. 6). The immediate pain relief observed may be attributed to the bactericidal effects of lasers, which can reduce the microbial load within the root canal system, thereby decreasing inflammation and pain[71,72]. However, the lack of sustained pain relief over longer periods suggests that the initial benefits of laser disinfection are transient.

The risk of bias assessment across the included studies indicated 'some concerns' (Fig. 2), primarily due to the limited number of studies available for certain comparisons and potential methodological weaknesses.

This demonstrated the need for more high-quality randomized controlled trials to confirm the efficacy of laser therapies in postoperative pain management.

From a clinical perspective, the findings suggest that while laser therapies, particularly LLLT and laser disinfection, can provide short-term pain relief following endodontic procedures, their long-term benefits are less clear. Practitioners may consider incorporating these modalities as adjunctive treatments for immediate postoperative pain management, especially in cases where conventional methods are insufficient. However, the limited long-term effectiveness observed warrants cautious application and emphasizes the need for continued research to optimize these therapies for clinical use.

In the present meta-analysis, the utilization of Er: YAG laser, particularly through the activation of irrigation solution, has emerged as a more efficacious approach when compared to other laser treatment modalities. This superiority can be attributed to the fact that laser systems, such as the Er: YAG laser, result in minimal extrusion of the irrigation solution from the apical foramen[73,74]. This reduced liquid extrusion is of significant advantage, as excessive extrusion may precipitate postoperative complications. Furthermore, laser-activated irrigation techniques have been demonstrated to generate remarkably low intra-canal pressure, typically not exceeding central venous blood pressure (approximately 5.88 mmHg)[75,76] The maintenance of such low intra-canal pressure is considered advantageous as it mitigates the risk of complications associated with high-pressure irrigation. Additionally, as previously elucidated, lasers in general, and laser-activated irrigation specifically, have shown effectiveness in eradicating and disinfecting bacteria within the root canal system, notably eliminating *Enterococcus faecalis*, a common bacterium found in infected root canals[77,78]. This antimicrobial action not only contributes to enhanced disinfection during RCT procedures but also potentially results in diminished postoperative pain originated form these ETT. However, it is necessary to acknowledge that further clinical studies directly comparing these different laser treatment modalities are requisite to draw a definitive conclusion regarding their comparative effectiveness in reducing postoperative pain in endodontic procedures[79,80].

Moreover, the meta-regression analysis identified tooth position as the only factor with a statistically significant influence on the outcomes of laser treatments in endodontics, with upper maxillary teeth achieving superior results. This suggests that maxillary anterior teeth experienced significantly less postoperative pain, potentially due to the cancellous nature of the maxillary bone allowing for better laser penetration and more effective treatment and the anatomical and physiological characteristics of maxillary teeth, such as their vascularization and neural networks, may contribute to the observed pain reduction[81,82]. While this is the best available evidence within the limitations of our review, further research is needed to confirm these findings and elucidate the underlying mechanisms. To sum up, this meta-analysis cautiously underscores the potential of intraoral laser therapies to enhance short-term pain management after endodontic treatments.

Limitations of the secondary study

This systematic review does have some limitations, primarily originating from the grouping of various laser treatment modalities into a single category. It can be argued that the diverse applications of laser in distinct manners warrant separate examination, given the substantial differences in their mode of application. While these therapies outperform placebo and show promise in the immediate postoperative period, their long-term benefits remain uncertain.

Some conventional groups in the primary studies may include ultrasonic cleansing[22,52,54] introducing a potential confounding factor as it represents an additional evaluated step.

Consequently, a comprehensive exploration of all potential prognostic factors was not feasible, despite the observed statistical homogeneity across the studies. Moreover, the absence of studies directly comparing these distinct laser treatment modalities presents a limitation.

Recommendations for future research

As a prospective recommendation for future research, it is advisable to conduct randomized clinical trials that rigorously compare the diverse laser treatment modalities within a standardized setting. These trials should establish specific parameters for laser utilization, employ a consistent tool for documenting postoperative pain, and implement strict inclusion criteria to differentiate between symptomatic and asymptomatic patients. Such an approach would contribute to a better understanding of the comparative effectiveness of these laser modalities and potentially address the limitations found in this review. Also, future research should focus on exploring the mechanisms underlying the transient effects of laser treatments to develop more effective and sustained pain management strategies in endodontics.

Conclusions

Our review assessed the efficacy of laser-based treatments for postoperative pain management in primary and secondary root canal therapies, concluding that:

- Intraoral laser therapy showed no significant advantage over conventional treatments but consistently outperformed placebo and was truly beneficial when combined with controls from 4 to 72 h.
- Low-level laser therapy provided slight pain reduction during the first 8 h post-treatment, with decreased effectiveness in retreatment scenarios.
- Photodynamic therapy marginally outperformed conventional treatment and placebo at 24–30 h.
- Laser disinfection achieved significant pain relief shortly after treatment, especially in early postoperative periods, with reduced benefits in longer-term or retreatment scenarios.
- Meta-regression analysis indicated lasers significantly reduced pain compared to placebo, showing a 32.4% higher rate of 'no/mild pain' in the laser group ($p=0.036$). Additionally, there were significant improvements with lasers, with a 28.9% increase in 'no/mild pain' rates compared to combined controls ($p=0.026$).

- Studies included had 'some concerns' regarding bias, with some analyses based on a limited number of studies.
- A significant influence of tooth position as a prognostic factor was observed, with maxillary anterior teeth displaying improved outcomes with laser treatment modalities.

Therefore, the best evidence showed that potential benefits of laser treatments in reducing postoperative pain following root canal therapies. However, further research, including randomized clinical trials with standardized methodologies, is needed to explore the various laser applications and impacts of distinct prognostic factors in greater depth.

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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