META-ANALYSIS

Meta-analysis of the Efficacy of Photodynamic Therapy (PDT) in the Treatment of Peri-implantitis

Shuangxi Liu, MM; Binping Wang, BM; Zhuogeng Chen, MM; Hui Mo, BM; Min Lin, BM; Xieshan Huang, MM

ABSTRACT

Objective • This meta-analysis aims to evaluate the comparative clinical efficacy of photodynamic therapy (PDT) versus other non-surgical treatments in managing peri-implantitis.

Methods • Computer searches were conducted in databases including PubMed, The Cochrane Library, Embase, China National Knowledge Infrastructure (CNKI), VIP, and Wanfang for randomized controlled trials (RCTs) on the clinical efficacy of Photodynamic Therapy (PDT) compared to other non-surgical methods in the treatment of peri-implantitis. The search period spanned from May 2000 to May 2023. Based on inclusion and exclusion criteria, literature was screened, data extracted, and the quality of the studies was assessed. Included studies were publicly published randomized controlled experiments focusing on the combination of photodynamic therapy and non-surgical methods compared to non-surgical methods alone in the treatment of peri-implantitis. Articles with insufficient or unclear definitions of peri-implantitis cases were excluded from the selected studies. Statistical analysis was performed using RevMan 5.3 software.

Results • Nine RCTs were included for Meta-analysis. Meta-analysis showed that patients in the PDT trial group had reduced peri-implant probing depth (PD) during the follow-up period compared with the control group [WMD=-0.40, 95%CI(-0.62,-0.17), P = .0005], and bleeding on probing (BOP) was reduced [WMD=-9.20, 95%CI(-13.69,-4.71), P < .0001] more significantly, and the difference between the two groups was statistically significant (P < .05); while for Modified plaque index (mPI) decreased [MD=-0.07, 95%CI (-0.16, 0.01), P = .09], clinical attachment loss (CAL) gained [WMD=-0.66, 95%CI:(-1.46, 0.14), P = .11]. Plaque index (PI%) decreased [WMD=-1.66, 95%CI:(-3.43, 0.11), P = .07] insignificantly, and the difference between the two groups was not statistically significant (P > .05).Photodynamic Therapy (PDT) has been significantly effective in reducing periodontal pocket depth and gingival bleeding in the treatment of periodontal diseases. However, its efficacy in improving plaque control and promoting tooth attachment is limited, which may be attributed to its primary antibacterial action rather than promoting tissue repair.

Conclusion • Compared to other non-surgical treatments, PDT treatment has significant advantages in reducing peri-implant probing depth and bleeding in patients with peri-implantitis. These results suggest that PDT may be a more effective non-surgical option for reducing probing depth and bleeding in patients with peri-implantitis. Of course, future studies with larger sample sizes and longer follow-up periods are needed to confirm these findings. (*Altern Ther Health Med.* [E-pub ahead of print.])

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INTRODUCTION

Peri-implantitis is one of the common and serious complications after dental implant surgery, ranging from mucosal inflammation to attachment loss, bone integration destruction, and even implant loss.[1] With the increasing popularity of dental implant surgery, peri-implantitis has become a major postoperative challenge, affecting a significant number of patients. At the World Workshop in 2017, jointly hosted by the American Academy of Periodontology (AAP) and the European Federation of Periodontology (EFP), peri-implantitis was standardized and defined as an irreversible inflammatory reaction related to plaque and involving the soft and hard tissues around implants. This clear definition is crucial for the diagnosis and treatment of peri-implantitis, providing clinicians with a clear diagnostic framework. This categorization helps clinicians accurately identify peri-implantitis and implement

more effective treatments, adjusting the therapy based on the severity of the condition. Additionally, a unified classification standard provides a basis for research, aiding in a deeper understanding of the pathology and treatment methods of peri-implantitis. In the long term, this aids in developing more effective prevention and treatment strategies, improving patient outcomes. Besides the aforementioned symptoms, increased probing depth and progressive absorption of the alveolar bone crest on radiographic examination are also observed.[2,3] Studies show that the individual incidence rate of peri-implant mucositis can reach 19%-84%,[4] and as one of the most common complications after implantation, peri-implantitis occurs at a rate of 28%-56%.[5]

Treatment methods for peri-implantitis mainly include non-surgical and surgical treatments. The former includes mechanical debridement, drug treatment, etc., while the latter includes resective surgery, reconstructive surgery, etc.[6] Due to its minimal trauma, high safety, and good therapeutic effects, non-surgical treatment has become a major focus of current clinical research. Mechanical debridement (MD), with its low technical sensitivity and reduction of inflammation and plaque biofilm, has always been the preferred treatment for periodontal disease and peri-implantitis. It involves thorough debridement and scaling of the natural tooth or implant surface through manual scraping, ultrasonic cleaning, air abrasion, or a combination of these methods to control infection.[7,8] Although mechanical debridement is effective in treating peri-implantitis, its limitations include difficulty in completely removing deep bacteria, risk of recurrence, potential damage to surrounding healthy tissues, limited effect on severe lesions, long treatment cycles, and potential discomfort for patients. Therefore, other non-surgical treatments are often combined when treating peri-implantitis.

Photodynamic therapy (PDT), also known as photochemical therapy or antibacterial photodynamic therapy, combines low-energy lasers with photosensitizers. The photosensitizer, attached to tissue cells and activated under specific wavelength light exposure, interacts with oxygen molecules in tissues and cells to produce singlet oxygen or oxygen radicals and other active molecules, causing tissue or cell oxidative inactivation or oxidative damage, leading to tissue damage and bacterial elimination.[9] Compared to traditional mechanical debridement or antibiotic treatment, PDT offers a less invasive treatment option with minimal damage to surrounding tissues, addressing the limitations of mechanical debridement, such as difficulty in completely removing deep bacteria and high recurrence rates, while also reducing reliance on antibiotics and the potential for antibiotic resistance. Additionally, the relatively simple operation of PDT causes less discomfort to patients, enhancing their comfort and cooperation with the treatment. Thus, PDT demonstrates unique advantages in the treatment of peri-implantitis, especially in overcoming the limitations of traditional treatment methods, offering patients a more effective and gentle treatment option. Initially used primarily for the clinical treatment of cancer, acne, and port-wine stains,[10] PDT has increasingly been applied in the field of dentistry in recent years. Studies have shown that PDT can be an adjunctive treatment method for periodontal and endodontic therapy.[11] Given the varying and sometimes contradictory results regarding the efficacy of PDT in treating peri-implantitis in the literature, it is necessary to perform a meta-analysis to synthesize these research outcomes, providing a clearer understanding. It is essential to update the meta-analysis with the latest studies to reflect the current evidence status. This article aims to collect recent literature on photodynamic therapy for peri-implantitis, focusing on key clinical parameters such as probing depth, attachment level, and bleeding on probing, to provide evidence-based medical evidence for clinical application.

METHOD

Search strategy

The literature search was conducted in May 2023 in three databases (PubMed, Scopus and Embase) indexing terms with photodynamic therapy and peri-implantitis. The main MesH used in the search was as follows: 'Photodynamic therapy' OR 'Peri-implant disease', with no restriction on the language or date of publication. The search strategy used in PubMed is shown in Figure 1, and the search was updated in May 2023.

Literature inclusion and exclusion criteria

Inclusion criteria (1) Study type: a randomised controlled trial of photodynamic therapy combined with non-surgical methods versus non-surgical methods alone for the treatment of peri-implantitis; PDT combined with non-surgical treatment for the trial group and mechanical debridement (MD) for the control group; (2) Study subjects: adults aged 18 years and above; implant restorations completed ≥1 year and no loosening of the implant; no treatment in the 3 months prior to participation in the trial; no antibiotics or non-steroidal anti-inflammatory drugs in the 3 months prior to the treatment; no serious systemic

Figure 1. PubMed search strategy

#1 "Photodynamic therapy" [MeSH Terms]

#2 "Photochemotherapy" [MeSH Terms]

#3 "Antibacterial photodynamic therapy" [MeSH Terms]

#4 #1 OR #2 OR #3

#5 "Peri-implant disease" [MeSH Terms]

#6 "Peri-implant mucositis" [Title/Abstract]

#7 "Peri-implantitis" [Title/Abstract]

#8 #5 OR #6 OR #7

#9 #4 AND #8

systemic diseases in the subjects; and females are not in the period of pregnancy or breastfeeding; (3) Follow-up time ≥ 3 months; (4) The study subjects are patients suffering from peri-implantitis; (5) Outcome indicators: the amount of change in peri-implant probing depth (PD), clinical attachment loss (CAL), modified plaque index (mPLI), bleeding on probing (BOP), and plaque index (PI%) were used as clinical outcome indicators.

Exclusion criteria: (1) Inadequate or unclear case definition of peri-implantitis; (2) There were interventions that did not meet, such as self plaque control, surgical treatment, and antibiotic treatment in the control group; (3) Literature such as non-clinical randomised controlled trials, case reports, literature reviews, letters or commentaries, conference reports, retrospective studies, and dissertations; (4) Duplicates of published studies; (5) Studies with incomplete raw data.

Literature screening and information extraction

All relevant literature retrieved initially was extracted and organized according to the above inclusion and exclusion criteria. Researchers trained in evidence-based methodology independently screened the literature, extracted information, and cross-checked it according to the inclusion and exclusion criteria; in case of disagreement, agreement was reached through discussion or adjudication was assisted by another researcher. The following were included: (1) Study identification: name of the first author and year of publication; (2) Subject-related information: gender, age, smoking status; (3) Disease inclusion criteria; (4) Group data: follow-up time, sample size, interventions (treatment regimen), and available outcome indicators.

Quality evaluation of literature

In this study, we used the latest version of the Cochrane Handbook for Systematic Reviews of Interventions, version 5.1.0, to assess the quality of the included Randomized Controlled Trials (RCTs).[12] This handbook provides a comprehensive set of guidelines and standards for assessing the risk of bias in RCT studies. The specific assessment content includes the generation of random sequences, concealment of allocation schemes, blinding of participants and interveners, blinding of outcome assessors, completeness of outcome data, selective reporting of results, and other potential bias items. Each item is judged based on 'low risk of bias,' 'high risk of bias,' or 'unclear risk of bias.' The process of literature screening and data extraction was independently completed by researchers trained in evidence-based medical methods and cross-checked. In case of disagreements, a consensus was reached through discussion or with the assistance of a third researcher. In this way, we ensured that the quality assessment of the included studies was both systematic and objective, based on internationally recognized evaluation standards. Additionally, we paid particular attention to the risks of implementation bias, measurement bias, and follow-up bias in each study to ensure the reliability and validity of our analysis results. Most of the studies included in this meta-analysis described that all participants were informed and signed informed consent forms before the start of the trial and received ethical approval from the relevant institutional review boards.

Statistical methods

In this study, we employed RevMan 5.3 software for the meta-analysis. The reason for choosing this software lies in its widespread application in systematic reviews and meta-analyses in clinical research, particularly its distinct advantages in handling biomedical data. RevMan offers an intuitive interface and powerful statistical capabilities, efficiently processing both continuous and binary data, and supports the selection of various effect models and assessment of heterogeneity. For the analysis of continuous data, if the studies used the same measurement tools, we will use the Weighted Mean Difference (WMD); if different measurement tools were used, the Standardized Mean Difference (SMD) will be employed. Each effect size and its 95% confidence interval will be used for estimation. To accurately assess the heterogeneity among the included studies, we will initially utilize the Q statistic and I^2 test provided by RevMan. The choice between these two methods is based on the I^2 test providing a more detailed gradient division in estimating heterogeneity, thus more accurately reflecting the degree of differences between studies. The interpretation criteria for I^2 values are as follows: $I^2 \geq 0\%$, $I^2 \geq 25\%$, $I^2 \geq 50\%$, and $I^2 \geq 75\%$, representing no heterogeneity, mild heterogeneity, moderate heterogeneity, and high heterogeneity, respectively. In cases of low heterogeneity ($0\% \leq I^2 \leq 50\%$), a fixed-effect model will be used for statistical analysis; when heterogeneity is high ($I^2 > 50\%$), a random-effect model will be adopted. Additionally, to explore and explain the sources of data heterogeneity, we will adopt methods such as subgroup analysis, sensitivity analysis, and meta-regression. When heterogeneity is too high to conduct an effective meta-analysis, we will perform a descriptive analysis of each study. This methodological design aims to ensure that our meta-analysis results are both accurate and reliable, with high interpretability, providing valuable guidance for clinical practice.

RESULTS

Results of the literature search

The preliminary search obtained 314 pieces of literature, and 2 pieces of related literature were added through other means, totaling 316 pieces. After the EndNote X9 software was used to eliminate duplicates, 85 articles were obtained, and then 76 articles that did not meet the inclusion criteria were excluded after reading the titles, abstracts and full texts, and 9 articles were finally included; the screening process and the study profiles of the included articles are shown in Figure 2 and Table 1.[6,13-20] The risk of bias of the included studies was assessed by the assessment form recommended by the Co-chrane Evaluator's Handbook, and all included studies were of high quality, with a low risk of bias for implementation bias, measurement bias, and follow-up bias (Figure 3).

Table 1. Basic characteristics of the included literature (n=9)

Inclusion of studies	Type of study	Age (years)	Intervention		Specimen volume (person)		Follow-up time (months)	Incorporation of indicators
			Experimental group	Control group	Experimental group	Control group		
Bassetti, 2014[13]	RCT	58	SPT+PDT	SPT	20	20	0, 3, 6, 9, 12	PD, CAL, mPI
Schär, 2013[14]	RCT	58	PDT+MD	LDD+MD	20	20	0, 3	PD, CAL, mPI
Karimi, 2016[15]	RCT	52.8	MD+PDT	MD	15	15	1.5, 3	PD, CAL
Wang, 2019[16]	RCT	43.4	MD+PDT	MD	65	66	0, 3	PD, CAL, mPI
Al Amri, 2016[6]	RCT	53.6	MD+PDT	MD	34	33	0, 3, 12	BOP
Alqahtani, 2019[18]	RCT	54.2	MD+PDT	MD	49	49	0, 3, 12	PDBOPPI%
Labban, 2021[19]	RCT	50.4	MD+PDT	MD	24	24	0, 6	PDBOPPI%
Pourabbas, 2023[20]	RCT	37.5	MD+PDT	MD	26	26	0, 3	PDBOP
Almohareb, 2020[21]	RCT	51.7	MD+PDT	MD	20	20	0, 6, 12	PDCALPI%

Figure 2. Flowchart of literature screening

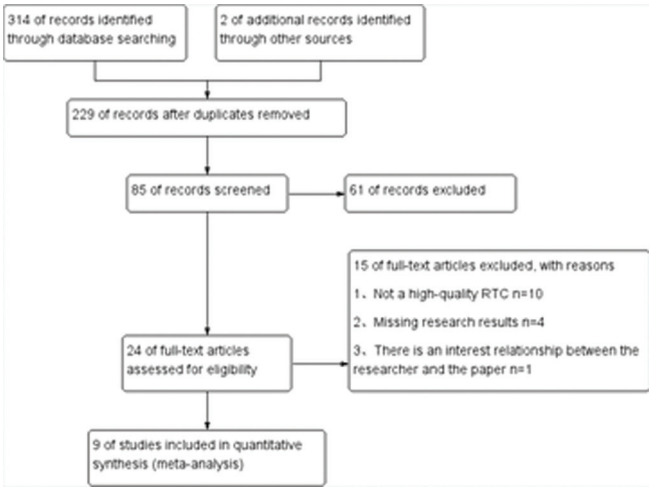


Figure 3. Risk of bias summary chart

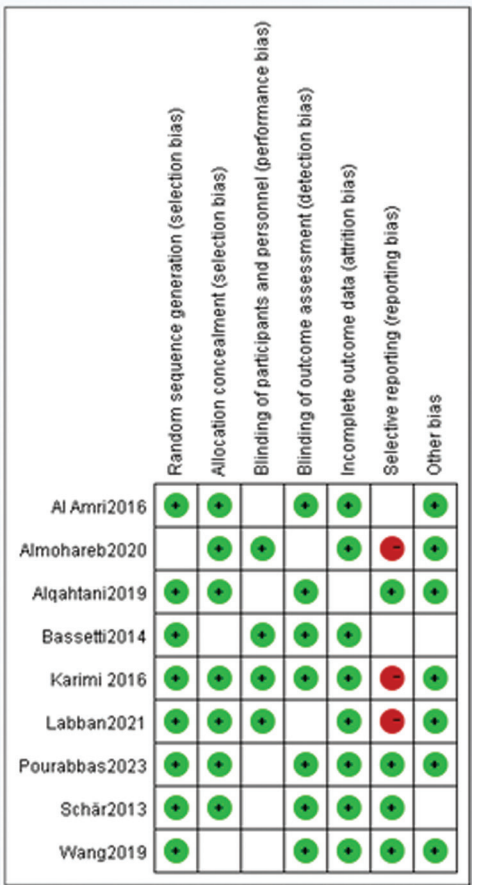


Figure 4. Effect of photodynamic therapy on peri-implant probing depths

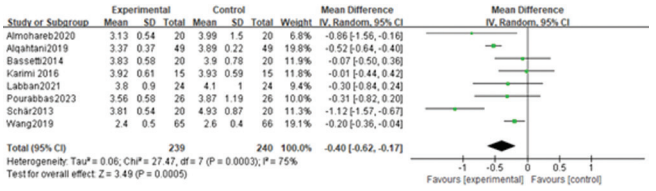
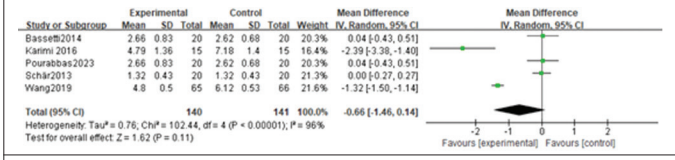


Figure 5. Effect of photodynamic therapy on CAL



Meta-analysis results

Effect of photodynamic therapy on peri-implant probing depth (PD). Eight papers reported the changes in PD, including 239 cases in the PDT group and 240 cases in the control group, and a random-effects model (I^2=75%) was chosen for Meta-analysis, which showed that the effect of PD in the PDT group was more significant compared with the control group. The difference was statistically significant [WMD=-0.40, 95%CI(-0.62,-0.17), P = .0005] (Figure 4), suggesting that PDT combined with MD significantly improved peri-implant probing depth compared to other non-surgical treatments.

Effect of photodynamic therapy on clinical attachment loss. A total of 5 studies were included in this paper to compare the effect of photodynamic therapy on CAL. There were 140 cases in the PDT group, and 141 cases in the control group, and the included studies were analyzed by software to obtain a forest plot of Meta-analysis of the effect of photodynamic therapy on CAL (Figure 5). The results showed that the heterogeneity test showed high heterogeneity between groups (I^2=96%), and using the random-effects model for calculation, its results showed that the incidence of CAL in the PDT group was not significantly different from that of the control group [WMD=-0.66, 95%CI:(-1.46, 0.14), P = .11]. In this section, the high heterogeneity observed in the analysis of Clinical Attachment Level (CAL) may stem from differences in baseline characteristics of patients, varying durations of treatment, or subtle differences in treatment methods. These factors could have affected the treatment outcomes, leading to significant variations in the results of the studies.

Effect of photodynamic therapy on bleeding on probing. A total of 4 studies were included in this paper to

compare the effect of photodynamic therapy on BOP. There were 127 cases in the PDT group and 126 cases in the control group, and the included studies were analysed by software to obtain a forest plot of Meta-analysis of the effect of photodynamic therapy on BOP (Figure 6). The results showed that the heterogeneity test showed high heterogeneity between the groups (I^2=72%), and using the random-effects model for calculation its results showed that the incidence of BOP in the PDT group was significantly different compared to the control group [WMD=-9.20, 95%CI:(-13.69, -4.71), P < .0001]. Despite the high heterogeneity in the analysis of BOP, after eliminating certain influencing factors, we still observed a consistent trend of PDT significantly reducing BOP. This highlights the potential value of PDT in improving periodontal health.

Figure 6. Effect of photodynamic therapy on bleeding on probing

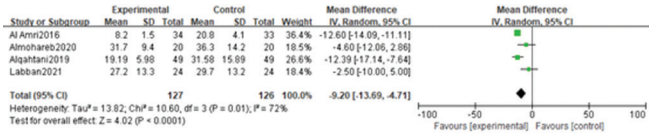


Figure 7. Effect of photodynamic therapy on modified plaque index

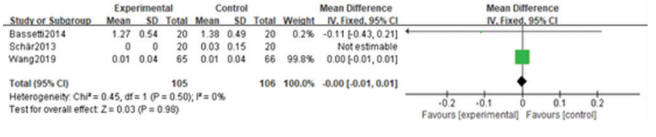
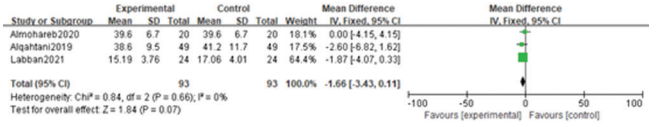


Figure 8. Effect of photodynamic therapy on plaque indices



Effect of photodynamic therapy on modified plaque index (mPI). A total of 3 studies were included in this paper to compare the effect of photodynamic therapy on mPI. There were 105 cases in the PDT group and the software analysed 106 cases in the control group, and the included studies to obtain a Meta-analysis forest plot of the effect of photodynamic therapy on mPI (Figure 7). The results showed that the heterogeneity test showed low heterogeneity between the groups (I^2=0%), and using the fixed effect model for its calculation its results showed that there was no significant difference in the incidence of mPI in the PDT group compared to the control group [WMD=-0.00, 95%CI:(-0.01, 0.01), P = .98].

Effect of photodynamic therapy on plaque indices. A total of three studies in this paper compared the effect of photodynamic therapy on PI. There were 93 cases in the PDT group and the softwarethe software analysed 93 cases in the control group, and the included studies analysed 93 cases in the control group, and the included studies to obtain a Meta-analysis forest plot of the effect of photodynamic therapy on PI (Figure 8). The results showed that the heterogeneity test showed low heterogeneity between the groups (I^2=0%). Using the fixed effect model for its calculation, its results showed that there was no significant difference in the incidence of PI in the PDT group compared to the control group [WMD=-1.66, 95%CI:(-3.43, 0.11), P = .07].The analysis results for Modified Plaque Index (mPI) and Plaque Index (PI) indicate that Photodynamic Therapy (PDT) and the control group have similar effects in reducing plaque formation. This may be related to PDT primarily targeting the elimination of deep bacteria rather than surface plaque control, or it could be due to the insufficient sample size of the studies to detect a significant difference.

DISCUSSION

Peri-implantitis is a common complication after dental implant surgery, with an incidence of 28%-56% reported in some studies.[1] Currently, the treatment of peri-implantitis includes mechanical treatment, medication, sandblasting, laser treatment and periodontal surgery.[3] However, due to the special threaded structure of the implant surface, traditional mechanical treatment instruments are prone to damage the oxidized layer on the implant surface, which reduces implant biocompatibility, increases plaque adhesion, and fails to achieve a satisfactory therapeutic effect.[5] Therefore, the traditional non-surgical treatment of mechanical debridement with topical antibiotics can no longer fully satisfy the treatment of peri-implantitis, and PDT is a new type of non-invasive photochemical control of infection, which is based on the principle that photosensitizers produce a large number of toxic active products under the irradiation of an appropriate source of light, destroying the biofilm of the cell or other functional units, and then leading to the death of the cells or microorganisms to achieve the therapeutic effect.[7] This systematic evaluation focuses on the depth of probing, probing haemorrhage, clinical attachment level and plaque index to assess the effectiveness of photodynamic therapy assisted mechanical cleaning in the treatment of peri-implantitis.For instance, the study by Sivaramakrishnan et al.[22] showed that PDT combined with mechanical debridement (MD) could significantly improve the Clinical Attachment Level (CAL) in patients with peri-implantitis, whereas in our study, the improvement in CAL by PDT was not significant. These differences might stem from variations in study designs, such as the sample size, baseline characteristics of patients (like the severity of the disease and implant type), and differences in PDT treatment protocols (such as the type of light source and photosensitizer dosage). Additionally, the duration of follow-up could also affect the results, with most studies in this research having follow-up periods of 3 to 6 months, while long-term follow-ups might reveal different effects. Therefore, future research needs to pay more attention to these factors for a more accurate assessment of PDT's effectiveness in treating peri-implantitis.

Meta-analysis showed that PDT combined with MD treatment improved the PD and BOP of patients with peri-

implantitis more significantly in the follow-up period compared with MD treatment, and the difference was statistically significant ($P < .05$), whereas the differences in mPI, CAL, and PI% were not statistically significant ($P > .05$), suggesting that the adjunctive application of PDT is more effective in reducing probing depth and probing bleeding in patients with peri-implantitis in the short term. This is consistent with the findings of Al Amri et al.[6] and Bassetti et al.[13] However, contrary to the Meta-analysis results obtained by Sivaramakrishnan et al.[21] the paper showed that PDT combined with MD significantly improved CAL in patients with peri-implantitis compared to other interventions, while there was no significant improvement in PD, mPI and BOP indices. The reasons for this may be related to the lack of a comprehensive literature search, the insufficient sample size of the included studies, and the lack of uniformity in the follow-up period. Karimi et al.[15] found that PDT combined with non-surgical treatment was more effective than non-surgical treatment alone in improving the PD, BOP, and CAL of peri-implant tissues in peri-implant inflammation patients after a 3-month follow-up period. However, Albaker et al.[22] concluded that PDT combined with non-surgical treatment was not more effective than non-surgical treatment alone in improving peri-implant inflammatory parameters. In some analyses of this study, we found a high level of heterogeneity, especially in terms of Probing Depth (PD) and Modified Sulcus Bleeding Index (mSBI). This high heterogeneity could stem from multiple factors. First, differences in PDT application parameters such as the type of photosensitizer, concentration, irradiation time, and light source intensity could lead to variations in treatment effects. Secondly, patient characteristics might also be an important factor. For instance, the severity of peri-implantitis, the age of patients, tobacco use, and oral hygiene habits could all impact the effectiveness of PDT. Finally, differences in research methodology, such as the length of follow-up, consistency of assessment methods, and the strictness of inclusion criteria, might also contribute to the heterogeneity of results. Future studies need more refined control in these aspects to reduce differences in outcomes, thereby enhancing the reliability of conclusions. Therefore, further long-term, large-scale, high-quality randomized controlled trials are required to corroborate these conclusions.

A large number of literatures have confirmed that PDT can be used as an adjunct to treat periodontal diseases. However, its efficacy in the treatment of peri-implantitis is controversial. This systematic review mainly evaluated the effect of photodynamic therapy assisted mechanical scaling in the treatment of peri-implantitis from the aspects of probing depth, bleeding on probing, clinical attachment level and plaque index. The current evaluation of the efficacy of PDT in the treatment of peri-implantitis lacks a longer follow-up period. Therefore, more long-term studies are needed to verify the efficacy of PDT in the treatment of peri-implantitis. The results of the heterogeneity test in the present study showed a high degree of heterogeneity between the literature included in the PD and mSBI studies, which may be related to the different types of peri-implantitis in the included subjects, the inconsistency in smoking status and duration of follow-up, and the different parameters of the application of PDT in the various studies. It is interesting to consider that there was a significant difference between the baseline levels of the included studies, which may have been related to the different severity of peri-implantitis or the inconsistency of the positions of the teeth included in the studies. In this study, the follow-up time of most studies was 3 months or 6 months, but there were few studies with longer duration, which is not good for our understanding of the long-term efficacy of PDT. In the future, more RCTs with large sample size should extend the follow-up time and pay attention to the differences in the long-term efficacy of PDT. At the same time, there is no uniform demographic standard for the subjects included in the relevant literature, and there are differences in ethnicity, region, age and education level. Future RCTs should reduce these differences. Compared with the traditional antibacterial therapy, photodynamic therapy has the advantages of minimally invasive, short action time, small side effects, high selectivity, avoiding bacterial resistance and penetrating into the parts that are difficult to reach by conventional instruments. In the short and medium term, photodynamic therapy has obvious advantages in the peri-implant probing depth and bleeding on probing compared with simple non-surgical treatment. It is expected to be a new adjuvant treatment for peri-implantitis, but there is no significant difference in improving the inflammatory indicators around the implant. Therefore, more long-term, large-scale and high-quality randomized controlled trials are needed for verification in the future. Of course, this study still has some limitations: (1) Only some literatures mentioned the method of generating random sequence and the method of allocation concealment, which may have selective bias; (2) The sample size of the included studies was relatively small, which may lead to insufficient test power; (3) In the detection of clinical indicators, the outcome assessors may have subjective factors, so there is the possibility of other bias; (4) This study only searched published articles in English and Chinese, and some articles that were not published in time due to negative results were not included, which may have publication bias. The clinical significance of the results of this study lies in demonstrating the potential of Photodynamic Therapy (PDT) in improving Probing Depth (PD) and Bleeding on Probing (BOP) in patients with peri-implantitis. This advantage of PDT may change the current methods of treating peri-implantitis. Compared to traditional mechanical debridement and drug therapy, PDT offers a non-invasive treatment option with fewer side effects, which is particularly important for patients who are ineffective or intolerant to traditional treatments. In routine clinical practice, the use of PDT not only reduces dependence on antibiotics but also decreases the risk of bacterial resistance. Additionally, the rapid and selective action mechanism of PDT helps enhance treatment effectiveness while reducing damage to surrounding

healthy tissues. Since PDT can penetrate areas that are difficult to reach with conventional mechanical debridement, it offers new possibilities for treating deep peri-implantitis. However, despite the potential of PDT in treating peri-implantitis, its cost-effectiveness and patient acceptance in clinical practice must be considered. In summary, as an adjunctive method for treating peri-implantitis, PDT may significantly impact improving clinical treatment outcomes for patients in the future. Nevertheless, we must acknowledge that PDT may have limitations in addressing all aspects of peri-implantitis, especially in terms of bone tissue changes. Current research has not fully revealed the effects of PDT on improving or reversing damage to peri-implant bone tissue. Bearing this in mind, it is suggested that when implementing PDT, it should be part of a more comprehensive treatment plan for peri-implantitis. For instance, PDT can be combined with traditional mechanical debridement, drug therapy, or even periodontal surgery to enhance treatment outcomes. Additionally, given the advantages of PDT in controlling local infection and inflammation, it can serve as an adjunctive method to alleviate symptoms, while physicians should use other treatment methods to address bone tissue issues around implants. Future research should explore the synergistic effects of PDT with these treatment methods and how to integrate PDT more effectively into comprehensive treatment plans in clinical practice.

In this study, we tried our best to avoid the potential risk of statistical heterogeneity and to ensure that our results were stable and reliable, but there are still some risks caused by clinical and methodological heterogeneity: (1) Only published literature was statistically analyzed in this study, and there is the possibility of publication bias due to the fact that negative results were not published in time or that literature in other languages was not included; (2) Potential heterogeneity among studies, such as differences in demographics, study design, implant surface characteristics, baseline values, and testing methods, may affect the results of the analysis, and there is a possibility of other biases; (3) Included literature lacked microbiological testing and imaging of bone tissue changes related to the endpoints; (4) The number of relevant literature for some of the endpoints was too small to obtain raw data for some of the literature. Therefore, the role and effect of photodynamic therapy in the treatment of peri-implantitis still need to be confirmed by studies with larger samples, longer follow-up time and more rigorous design to evaluate its long-term efficacy in this field.

CONFLICT OF INTEREST

The authors have no potential conflicts of interest to report relevant to this article.

FUNDING

This study did not receive any funding in any form.

AUTHOR CONTRIBUTIONS

SL and XH designed the study and performed the experiments, BW and ZC collected the data, HM and ML analyzed the data, SL and XH prepared the manuscript. All authors read and approved the final manuscript.

ETHICAL COMPLIANCE

Not applicable.

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