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REVIEW

# Advances in Photoelectric Therapy for the Early Intervention and Treatment of Traumatic Scars

Qi Tian[1,2,*], Yi-Xin Zhang[3,*], Jin-Jing Wang[4,*], Guo-Bao Huang[2]

[1]Department of Clinical Medicine, Weifang Medical University, Weifang, People's Republic of China; [2]Department of Burns and Reconstructive Surgery, Central Hospital Affiliated to Shandong First Medical University, Jinan, People's Republic of China; [3]Centre for Translational Medicine, Institute of Precision Medicine, The First Affiliated Hospital, Sun Yat-sen University, Guangzhou, People's Republic of China; [4]Department of Surgery, Central Hospital Affiliated to Shandong First Medical University, Jinan, People's Republic of China

*These authors contributed equally to this work

Correspondence: Guo-Bao Huang, Department of Burns and Reconstructive Surgery, Central Hospital Affiliated to Shandong First Medical University, No. 105, Jiefang Road, Lixia District, Jinan, Shandong Province, 250013, People's Republic of China, Tel +86 531-55865707, Email huangguobao@sdu.edu.cn

**Abstract:** Traumatic scar is a disease that affected approximately tens of millions of patients worldwide. According to the histological and morphological properties of scars, the traumatic scar typically includes superficial scar, atrophic scar, hypertrophic scar, and keloid. Its formation is a natural consequence of wound healing, regardless of whether the wound was caused by trauma or surgery. However, the production of scars has considerable impacts on the physical and mental health of patients, even causing substantial aesthetic and functional impairments. Prevention or early treatment of scars is the most suitable therapeutic method, including surgical and non-surgical procedures; nevertheless, the benefits of non-operative therapies for scars are quite limited, and surgical treatments are always hard to achieve satisfying outcomes. Through the application of innovative technologies such as lasers, intense pulsed light, and radiofrequency, significant progress has been made in the treatment of traumatic scars. This review highlights the current advancements of photoelectric therapy for the prevention and treatment of various traumatic scars, which may throw light on innovative therapeutic options for scar therapies.

**Keywords:** scars, photoelectric therapy, lasers, intense pulsed light, radiofrequency

## Introduction

Traumatic scars are inevitable consequences of healing in skin and soft tissue after various injuries, including rubbing or scraping, sharp objects piercing the skin, and thermal or chemical burns.[1] It affected approximately tens of millions of patients worldwide, with common morbidities such as itching, pain, contracture-related facial malformations, and even reduced range of motion in the functioning joints.[2,3] These physiological problems always bring low self-esteem, depression and anxiety disorders, and posttraumatic stress disorder to these patients, especially in the world of the increasing demands of beauty.[4] Thus, early intervention and treatment of scars are imperative to shorten the immature period of scars and effectively control the development of scars, thereby decreasing the incidence of morbidities and psychological problems.

The surgical and non-surgical approaches are the current treatment options for the treatment and management of scars.[5] In detail, surgery is always used to address inadequacies and abnormalities and is particularly useful in patients with functional impairment caused by scar contracture. Nevertheless, the high recurrence rate (more than 40%) has compelled the implementation of adjuvant chemotherapy after surgery.[6] The non-surgical techniques mainly include photoelectric therapy, radiation therapy, silicone products, intralesional injection of steroids or other medicines, compression garments, etc. However, many of these therapies in clinical practice remain suboptimal. For example, it is believed that silicone products can effectively limit the hyperplasia of scars, improve pliability, and reduce scarring incidence,[7] but inconsistent findings from recent research have made it difficult to draw a firm judgment about whether the data supports the use of silicone treatment.[8,9] Moreover, patients with scars can be benefited from local injections of glucocorticoids to



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reduce the area of scars and uncomfortable symptoms, but it may be related to many inadequately studied systemic effects, such as osteoporosis, Cushingoid syndrome, and immunosuppression.[10] These limitations make the development of novel treatment options and majorization of the current treatment protocols urgent.

In recent years, clinicians have witnessed advances in the aesthetics and functionality of treating traumatic scars with photoelectric therapy, offering convenience for medical staff and benefits including little invasion, quick healing, and reduced risk of scar treatment for patients. This review will summarize the advances in photoelectric therapy for the early intervention and treatment of different traumatic scars. Hopefully, this review can serve as a guide for therapeutic applications as well as future clinical and basic research.

## Classification and Evaluation of Traumatic Scars

According to the histological and morphological characteristics, scars can be typically categorized as superficial scar, atrophic scar, hypertrophic scar, and keloid.[11] Injuries (eg, trauma, surgery, etc.) and chronic inflammation (eg, acne, etc.) that damage dermal collagen and/or subcutaneous tissue are the main causes of the first two, also known as non-hypertrophic scars.[12] They can come into touch with deep muscles and tendons, and can be either firm or soft, flat or just slightly higher or lower than the surrounding skin surface.[13] Moreover, the reticular dermis layer, which displays excessive angiogenesis, ongoing inflammation, and significant collagen buildup, is where hypertrophic scars and keloids originate.[14] Traditional hypertrophic scars only have nodules, whereas classic keloids spread aggressively, rarely go away on their own, and contain keloidal collagen at the histologic level.[15] Studies have suggested that keloids and traditional hypertrophic scars are two extreme manifestations of the same skin disorder because many scars exhibit the pathologic and clinical characteristics of both of them.[16]

These different types of scars should be comprehensively evaluated before photoelectric therapy, including medical history, family history, local symptoms and signs of scar (color and texture) etc.[17] In order to facilitate the clinical application of photoelectric technology in the treatment of scars, it is recommended that patients with traumatic scars should be evaluated based on the scar color (red or not red), location (limbs, face, or other lesions), type (hypertrophic, non-hyperplastic), and patient characteristics (eg, skin type, psychological expectations) to guide clinicians to choose the appropriate treatment plan, photoelectric equipment, and monitor the treatment effects.[18]

## Laser

### Pulsed Dye Laser

Pulsed Dye Laser (PDL, wavelength 585/595 nm) works by selectively photolyzing scar tissue in order to break down microvessels in scars and prevent their growth.[19] As red is the PDL's target chromophore, the laser's light energy is directed at the chromophore in oxyhemoglobin, where it is absorbed and transformed into heat energy, resulting in coagulation necrosis.[20] PDL is typically used in early hyperemic scars to limit early scar development and lessen erythema since it can disrupt the microvascular structure.[21] Deng et al demonstrated that PDL (585 nm) effectively decreased the thickness of immature hypertrophic scar, scar erythema, and blood perfusion in 45 patients with immature hypertrophic scar.[22] Ouyang et al found that patients' new trauma scars seem to be benefited clinically from the use of 595 nm tunable PDL.[23] Furthermore, Kim et al showed that when eight treatment sessions with the 595 nm PDL (with the dosage gradually raised by 0.5 $J/cm^2$) were administered to 19 patients with hypertrophic scars following thyroid surgery at intervals of 4 to 6 weeks, significant improvements were observed in the mean height, pigmentation, and vascularity ratings.[24] A randomized, controlled trial also found in 40 individuals (41 scars) who had undergone postoperative knee arthroplasties, the areas that had been laser-treated obtained considerably higher scores across the board for the Vancouver scar scale (VSS), suggesting the 595 nm PDL was a reliable and secure therapeutic alternative for the treatment of surgical scars left over from a knee arthroplasty.[25] A meta-analysis also suggested that PDL may be a secure and efficient way to repair surgical scars, because PDL substantially reduced the VSS scores in height, vascularity, pliability, and pigmentation, with no overtly harmful impacts on the majority of persons.[26] To treat hypertrophic burn scars in Chinese children with Fitzpatrick skin types III and IV, a retrospective research was conducted to determine the best PDL therapy settings and indicated that early intervention, sensible treatment intervals, and modest PDL fluence were ideal.[27]

## Diode Laser

Diode laser can dramatically speed up wound healing by activating tissue regeneration, reducing scarring, and inducing the expression of heat shock proteins (HSP70) in the epidermis and dermis around the lesion by thermal impacts.[28] In a prospective cohort study by Li et al, 21 patients with hypertrophic scars or keloids were treated with 1 to 3 sessions of the intralesional 1470 nm bare-fiber diode laser. The results showed that the hypertrophic and keloid scars significantly improved with no side effects, including skin infection, hypo/hyperpigmentation, or recurrence.[29] In a research by Mohsen et al, it was discovered that using a diode laser with a wavelength of 806 nm and a power of 100 mw greatly improved the pigmentation, height, pliability, and vascularity of the scars on 80 patients who had cleft lip scars.[30] Another study for a total of 19 patients who have a history of inflamed keloids with episodes of infection or abscess demonstrated that 1470 nm fiber laser treatment could improve inflamed keloids fairly well by decreasing inflammation, and relative stabilization of collagen composition. Therefore, it is an effective minimally invasive scar therapy.[31] Casanova found that after bilateral breast reduction surgery, a portable 1210 nm diode laser was employed in 40 female patients. It was applied to one breast right away after surgery, while the other breast served as the control for the experiment. The findings demonstrated that diode laser can improve the scars' volume, look, and roughness, with no negative side effects.[32]

## Ablative Fractional Laser

Ablative fractional laser (AFL) mainly includes fractional $CO_2$ laser (wavelength: 10,600 nm) and erbium:yttrium-aluminium-garnet (Er:YAG) laser (wavelength: 2940 nm). Current studies found that AFL is not only just used to treat mature scars: during the first stages of the wound and burn healing, AFL may not only drastically lessen the scar formation but also reduce scar thickness and improve the appearance and function.[33] A meta-analysis of 25 studies also concluded that fractional $CO_2$ laser treatment considerably reduced the signs and symptoms of burn scars as determined by both objective and subjective tools.[34] Another meta-analysis that included 8 research found that although treatment protocols differed across them, fractional $CO_2$ ablative laser therapy resulted in an average VSS improvement of 29% among 282 patients.[35] On both patient- and observer-rated measurements, Patel et al convincingly demonstrated that $CO_2$-AFL treatment reduces hypertrophic burn scars of pediatric patients, demonstrating that $CO_2$-AFL may repair hypertrophic burn scars in children and offering a less intrusive, more effective alternative to invasive therapies as well as a more quick and immediate option than more traditional scar treatments.[36] Moreover, patients with hypertrophic scars who had $CO_2$-AFL treatment reported considerably better sleep quality and less discomfort and itchiness.[37] Furthermore, Radmanesh et al found PDL and fractional $CO_2$ laser were similarly effective.[38] Elgarhy et al also found in 30 patients with old hypertrophic scars, both PDL and the ablative fractional $CO_2$ laser were successful in treating old hypertrophic scars; however, the latter approach was more effective in reducing the pliability and height of scars.[39]

In terms of Er:YAG laser, thermal burn scars may be effectively treated using it, which can also improve both the patient's and the doctor's perceptions of the condition.[40] A randomized controlled study revealed that fractional Er:YAG laser (2940 nm) and micro-needling are equally safe and effective for post-traumatic atrophic scars, but the latter approach requires more frequent sessions to provide satisfactory results that are comparable to those of fractional lasers.[41] In the patients with scars caused by self-inflicted injury using razor blades, Er:YAG was a secure and efficient option for them, but they needed multiple treatments and increasing joules in every session.[42]

## Non-Ablative Fractional Laser

Unlike AFL, non-ablative fractional laser (NAFL) can target just the dermal tissue under the skin's surface, heating it by infrared radiation without harming the epidermis. It is often used in combination with other treatments when treating scars. In terms of the treatment of hypertrophic scars and keloids, Shin et al found the combination therapy using a NAFL and intralesional steroid injection had superior outcomes with fewer treatment sessions, higher patient satisfaction, and longer remission times.[44] A prospective, randomized, blinded pilot study also demonstrated that such a combination treatment decreased the discomfort, itchiness, pliability, thickness, and alleviation of scars.[45] Guo et al suggested that the combination of a low dosage local application of compound betamethasone with a 1565 nm NAFL can significantly enhance the immature red hypertrophic scars with no negative side effects, giving practitioners a new tool to combat difficult-to-treat early scar forms.[46] Moreover, the efficient production of post-epicanthoplasty scars can be enhanced by early NAFL therapy in conjunction with silicones.[47] Besides, Taheri et al discovered that NAFL (1540 nm) is a viable and secure treatment option for atrophic cutaneous leishmaniasis scars which is one of the endemic illnesses in Iran, especially in those with darker skin.[48]

## Intense Pulsed Light

Intense pulsed light (IPL) can penetrate the skin and be selectively absorbed by hemoglobin. Then, it inhibits scar hyperplasia by denaturing and coagulating hemoglobin, damaging the vascular endothelial cells in the scar, and occluding the blood vessels.[49] A study that included 28 patients with hypertrophic scars who either had cryotherapy or IPL, showed that cryotherapy is more successful than IPL in treating hypertrophic scars on both a clinical and histological level, however, it comes with additional risks.[50] In a research conducted in Turkey, patients with hypertrophic scars and keloids were treated with an average of eight IPL, and more than 90% of patients showed substantial improvement in the height, erythema, and hardness of their scars.[51] Another study found in 37 patients with burn scars, the narrow-spectrum IPL can improve 93.75% of scars.[52]

## Micro-Plasma Radio-Frequency Technology

Micro-plasma radio-frequency (RF) is an approach that micro-exfoliates the epidermis to promote rapid epithelialization and produces a thermal effect on the dermis, thereby stimulating the fibroblast regeneration.[53] Compared with other photoelectric therapies, Micro-plasma RF has exact curative effects, fewer adverse reactions, and shorter recovery time, and has been widely used in the treatment of early scars and mature scars.[54] Zhang et al used 6 New Zealand white rabbits to generate a total of seventy-two hypertrophic scar models in the rabbits' ears, then randomly separated them into experimental and control groups. A month following the successful construction of the model, the experimental group was treated with micro-plasma RF. After 30 days of therapy, the number of scar micro-vessels, interleukin-8 (IL-8), and monocyte chemoattractant protein-1 (MCP-1) dropped considerably in comparison to the control group, and the micro-vessel density was positively linked with the expression of IL-8 and MCP-1 in both groups.[55]

## Combination Therapy

Combination treatments are commonly used in the treatment of scars. Song et al assessed the efficacy of early combined AFL and PDL therapy after scar revision. In the group of 14 patients who had scar correction and a total of 4 treatments using a 10,600-nm AFL and a 595-nm PDL, starting 2 weeks after scar revision and continuing every 4 weeks thereafter, all VSS scores dramatically improved with the exception of scar height. Besides, during follow-up, these patients experienced no negative side effects (wound disruption, hyper- or hypopigmentation). It suggested that early combined $CO_2$ AFL and PDL therapy successfully and safely reduced scar formation.[56] Matuszczak et al demonstrated unequivocally that PDL combined fractional $CO_2$ laser for burn scars can enhance their texture, color, and function. A prospective, randomized control trial found in comparison to control and $CO_2$ laser alone, treatment with a combination of IPL and fractional $CO_2$ laser showed greater average improvements in both texture and color across the majority of examined scar domains, indicating by employing a variety of wavelengths to target the different chromophores in scars, a multi-photo-thermolytic approach combining IPL with $CO_2$ AFL could be successful in treating hypertrophic scars.[57] However, Laura et al looked at hypertrophic burn scars of different ages, origins, and thicknesses. Although greater early decrease is seen in thicker scars when utilizing $CO_2$, PDL, or both laser modalities, there was no clinically significant advantage discovered comparing combined therapy to individual therapy.[58] Nevertheless, when inhibiting the early hypertrophic scar in rabbit ears, fractional $CO_2$ laser therapy has been demonstrated to be more effective than either pulsed dye laser treatment or $CO_2$ laser treatment alone.[59] Additionally, despite the use of a high-energy dosage of fractional $CO_2$ laser and an average of five sessions of treatment, patients with acne scars dramatically improved ECCA scores, minor pain experience, and low rates of side effects with the use of fractional $CO_2$ laser and fractional microneedle radiofrequency. Another study also performs a clinical trial on twenty patients with atrophic facial acne scars who were randomly split into two groups and given three monthly treatments each using an AFL with low energy plus a NAFL on one side of their faces and high and low energy lasers on the other. This study found that whilst utilizing an AFL with high intensity resulted in an improvement in patients' acne scars, it is noteworthy that the most optimal outcomes were achieved through the amalgamation of AFL and NAFL.[60] Furthermore, a randomized clinical trial with 30 patients who had keloids and hypertrophic scars found that treating keloids and hypertrophic scars with long-pulsed Nd:YAG laser is both efficient and safe. While keloids respond similarly to both fractional $CO_2$ and Nd:YAG laser treatment, hypertrophic scars respond better to fractional $CO_2$ laser treatment. Combination in the same session did not significantly increase the benefits, and its adverse effects were larger.[43]

Not only that, compared to single treatment of Er:YAG or no therapy, the combination of IPL and Er:YAG has shown more beneficial benefits on scar avoidance. In the early stages of wound healing, IPL/Er:YAG treatment may be a reliable and secure method for preventing the formation of scars.[61] Besides, both the combination of IPL and RF and the 1064-nm Nd:YAG laser were effective in treating hypertrophic scars, but only the combined method showed a substantial improvement in the clinical and histological findings.[62] Furthermore, Li et al found that fractional micro-plasma RF coupled with fractional ablative $CO_2$ laser is more successful than single therapy for the treatment of hypertrophic scars. Additionally, repeated therapies may increase the efficacy of combination therapy, and patients should be urged to seek treatment as soon as feasible.[63] To find the best technique for treating pathological scars, a network meta-analysis compared and ranked the effectiveness of laser and IPL treatments. It was shown that the combination of IPL and $CO_2$ laser has the greatest likelihood of being the most successful intervention.[64]

## Molecular Changes Induced by Photoelectric Therapy for Scars

Skin wound healing involves three phases: inflammation, proliferation, and regeneration. Abnormalities in these phases can result in various scarring. In terms of hypertrophic scar and keloid, inflammatory cells infiltrate the damaged area and release cytokines after injury, stimulating the migration and proliferation of keratinocytes and fibroblasts.[65] Fibroblasts secrete extracellular matrix (ECM) proteins (ie Collagen, fibronectin, hyaluronic acid, etc.), forming granulation tissue.[66] Increased vascularization and angiogenesis occur during the proliferation phase, which is heightened in hypertrophic scars.[67] Myofibroblasts, activated by transforming growth factor-β1 (TGF-β1), contract the wound and reduce its size.[68] Re-epithelization begins with keratinocyte proliferation and a decrease in blood vessels, leading to fewer fibroblasts in mature scar tissue.[69] In addition, studies have shown that atrophic scars' lack of thick collagen fiber deposition in the dermis may be due to an imbalance between collagen synthesis and breakdown, which is mediated by matrix metalloproteinases (MMPs) and their inhibitors.[70] Moreover, the degree and length of inflammation are also involved in the formation of atrophic scars, and the aberrant extracellular matrix metabolism may be impacted by exacerbated inflammation and aberrant epidermal proliferation caused by enhanced transforming growth factor 1 (TGF-1) signaling.[71] While improvements in scar thickness, color, and pliability were noticed one month following laser therapy, MMP-2 and TIMP-1 plasma levels also decreased.[70]

A series of metabolic alterations will be brought on by the photoelectric treatment. Histological studies showed that the fractional laser could initiate the inflammatory process, and MMPs and heat shock proteins controlled collagen formation and remodelling.[71] Ablative fractional $CO_2$ laser therapy was observed to improve the architecture of the skin layers, decrease collagen type I, and raise collagen type III, as well as reduce the plasma levels of metalloproteinase 1 (TIMP-1) and MMP-2 one month following laser treatment.[72] However, MMP-2 plasma levels could be increased soon after burn damage.[73] Furthermore, 585-nm PDL affected the signalling pathway and caused a breakdown of collagen and fibroblast death.[74] In this process, the metalloproteinases and IL-6 were activated hence the decrease of ECM, and transforming growth factor beta (TGF-β) and platelet-derived growth factor (PDGF) are blocked.[74] Moreover, in a rabbit model, the use of a fractional $CO_2$ laser with a 595-nm PDL can enhance the shape and histology of hypertrophic scars by reducing TGFβ1 and proliferating cell nuclear antigen (PCNA) protein expression.[75] In addition, another study found that the mRNA expression of MMP1, 2, and 3 as well as chemokines (Chemokine (C-X-C motif) ligand 1, 2, 5, and 6) and interleukins (IL-6, IL-8, and IL-24) was considerably higher in tissue samples obtained three days following fractional Er:YAG laser treatment.[76] In terms of the treatment of IPL, it suppressed levels of IL-6, tumor necrosis factor-


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alpha (TNF-α), MMPs, and proteolytic enzymes while raising levels of IL-10 and TGF-β in skin cells.[50,77] Overall, the continuous investigations of novel indications, technologies, and methods to enhance efficacy and safety were promising, but a deeper comprehension of the underlying mechanisms was still needed.

## Conclusions

Laser, IPL, and micro-plasma RF are effective and safe methods to improve the appearance of trauma scars, including erythema, texture, thickness, and pigmentation. These approaches can also alleviate unpleasant symptoms like pain and itching and improve the function of scar lesions, eliminating the need for surgical excision. It's recommended to consider these methods immediately after scar formation following wound healing, typically within one week after suture removal, to minimize scar development. Various photoelectric therapy devices can be used alone or in combination to treat scars and most studies indicate that combining different photoelectric therapies or scar treatment methods at an early stage may be more effective. However, due to the distinct characteristics and limitations of each photoelectric technology, the optimal treatment of traumatic scars with these technologies has not been fully optimized, and there are still many unanswered questions regarding the long-term consequences and effectiveness of various procedures. In addition, scar formation is a complex process that can be influenced by a multitude of factors, so the same photoelectric treatment may have varying effects on scars with different characteristics. Thus, healthcare professionals should consider various factors that influence scar formation when treating the scars, such as the type of trauma, genetics, skin type, and predilection or location where the scar occurs. In the future, larger-scale prospective clinical trials and physiological studies will be required to investigate the optimal treatment options for traumatic scars and the biological mechanism in order to promote the clinical practice of these techniques in the treatment of traumatic scars and to better understand these techniques.

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## Disclosure

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