



Laser tattoo removal: laser principles and an updated guide for clinicians

Loren Hernandez¹ · Noreen Mohsin¹ · Fabio Stefano Frech¹ · Isabella Dreyfuss² · Ashley Vander Does¹ · Keyvan Nouri¹

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Abstract

Tattoos have become ingrained in our society and have served varied purposes throughout human civilization. So long as tattoos have existed, there has been demand for their removal. Lasers are currently the modality of choice in the removal of tattoos, as they are more efficacious than previously used methods. The most common lasers are the 532 nm and 1064 nm neodymium-doped yttrium aluminum garnet lasers, the quality-switched 694 nm Ruby laser, and the quality-switched 755 nm alexandrite laser. However, picosecond lasers are rapidly gaining favor in tattoo removal. An in-depth understanding of laser principles and how they can be applied in the setting of tattoo removal is key. Also, a greater understanding of the origin of and colors within a tattoo, the presence of tattoo layering, and a patient's Fitzpatrick skin type increase the odds of satisfactory results. This review provides dermatologists with a comprehensive summary on laser fundamentals, an overview on treatment principles, and recent developments in the field of laser tattoo removal.

Keywords Tattoo · Laser · Tattoo removal · Picosecond

Introduction

Tattoos are a form of body modification involving the deposition of pigment in the skin's dermal layer. The process of tattooing has been practiced for thousands of years, with the earliest example dating 5200 years ago with "Otzi the Iceman," a glacier mummy with linear carbon tattoos thought to be performed for medicinal reasons [1]. Ancient tattooing was often performed for religious or ceremonial purposes, gradually transitioning to the primarily ornamental purpose they serve today. For some, tattoos are performed as a mode of self-expression, to describe a personal narrative, or even for no specific reason at all [2]. Tattoos may also be cosmetic in nature, with many individuals tattooing their eyebrows, lash line to serve as eyeliner, and lips.

Once considered taboo and associated with marginalized groups, tattoos are becoming more popular with a prevalence of over 10% in the USA [3, 4]. However, individuals may grow to regret their tattoos or desire removal for other reasons, such as acquiring a new job or career, a change in social status, medical problems, or dissatisfaction with their appearance or presence. A recent epidemiological study found that individuals belonging to racial and ethnic minorities, having gang affiliations, and/or having been formerly incarcerated are increasingly utilizing laser tattoo removal services [5].

According to the most recent American Society of Dermatologic Surgery (ASDS) on Dermatologic Procedures in 2019, over 164,000 laser tattoo removal procedures were performed by ASDS members [6]. Prior to the implementation of laser technology in the removal of tattoos, other techniques utilized include dermabrasion, cryosurgery, electrocauterization, and chemical peeling with salabrasion being the oldest method, dating back to 534 BC [7, 8]. However, these procedures often resulted in prolonged healing times and the formation of scar tissue [8]. Lasers were first implemented for tattoo removal in 1965 by Goldman et al., who tested the Q-switched (QS) Ruby laser on tattoos [9]. Subsequently, the tattoo removal landscape was forever changed,

✉ Loren Hernandez
loren.hernandez@med.miami.edu

¹ Dr. Phillip Frost Department of Dermatology and Cutaneous Surgery, Miller School of Medicine, University of Miami, 1600 NW 10th Ave, Miami, FL 33136, USA

² Nova Southeastern University, Patel College of Osteopathic Medicine, Dr. Kiran C, Fort Lauderdale, FL, USA

and lasers would become the mainstay of tattoo removal. This review article will touch upon the process of tattooing and the cutaneous response to tattoos, the fundamental principles of laser physics, provide dermatologists with a succinct guide for the appropriate selection of lasers in tattoo removal, and discuss recent updates in the field.

Process of tattooing and cutaneous response to tattoos

Tattoos are produced when pigment material is inserted into the skin's dermal layer. This ink is deposited in the lysosomes of macrophages, dermal mast cells, and fibroblasts [10]. It is the presence of pigment within these cells in the dermis that results in the permanent nature of tattoos. There are five major categories of tattoos. They include professional tattoos, amateur tattoos, cosmetic tattoos, traumatic tattoos, and medical tattoos [11]. Professional tattoos are typically performed with hollowed needles that deposit pigment via constant vibration [11, 12]. Amateur tattoos are completed with home machines or handheld devices with solid needles, only serving to deposit ink [13, 14]. Cosmetic tattoos include permanent lip liner and lipstick, eyeliner, and eyebrow makeup. This is undertaken to enhance facial features and it is done by a micropigmentation technique [15]. Traumatic tattoos are the result of the mechanical penetration of foreign particles such as glass, metal, and carbon-containing particles [12]. Medical tattoos are placed by medical personnel as a way to designate anatomic sites, such as port placement sites or radiotherapy fields [12].

After tattooing, patients may experience shedding of overlying epidermis with potential inflammation of the dermis; as such, tattoos are considered wounds of partial thickness [16]. Re-epithelialization of partial-thickness wounds originates from stem cell or progenitor cells in the eccrine sweat glands, pilosebaceous units, and interfollicular epidermis [17]. This process generally begins within 24 h after injury and involves immune cell recruitment to the site of injury followed by keratinocyte activation and proliferation [17]. Re-epithelialization may take 2 to 3 weeks to complete.

Up to 80% of pigments injected into the skin may no longer be detectable after several years [18]. There are several ways in which tattoo ink may leave the original tattoo site. Macrophages may uptake components of ink, which remains in lysosomal compartments within these immune cells [18]. Components of ink may also move through lymphatic vessels and drain into regional lymph nodes [18]. Several case reports have described how tattoo-pigmented lymph nodes have been mistaken for metastatic cancer [19]. Tattoo pigment remaining at the original site of tattooing may aggregate into crystals and is generally insoluble, which prevents enzymatic degradation [20].

Skin infections or allergic reactions, such as photoallergic dermatitis or allergic contact dermatitis, may occur after tattooing [21]. One study reported that up to 20% of tattoo ink may contain impurities, including harmful substances such as polycyclic aromatic hydrocarbons, and this finding may influence the occurrence of adverse reactions after tattooing [21, 22].

Laser physics and parameters

The theory of selective photothermolysis is the basis by which tattoo ink is removed via laser therapy. In selective photothermolysis, laser energy is absorbed by the target tissue. This causes the electrons of the targeted tissue to become excited and vibrate, producing thermal energy. Of note, only electrons of the same frequency as laser light will vibrate, hence its selectivity [23]. In laser tattoo removal, tattoo pigment serves as the target chromophore. Each pigment color absorbs light of a different wavelength, making certain lasers more appropriate in tattoo removal depending on the color, or lack thereof, in the patient's tattoo. Physicians must also consider the absorption of melanin when determining the most appropriate laser wavelength; melanin's absorption peaks range from 300 to 600 nm. This is especially important in patients with darker skin tones Fitzpatrick IV–VI, as melanin may be targeted in addition to tattoo pigment, potentially leading to dys- or hypopigmentation of the patient's skin.

Other terms that are important in the understanding of laser physics are pulse duration and thermal relaxation time. A laser's pulse duration refers to the amount of time tissue is exposed to laser energy [24]. The thermal relaxation time describes the amount of time required for the target tissue to reach half of its peak temperature after laser exposure [24]. For optimal tattoo removal and to minimize thermal damage, the laser's pulse duration should be less than the thermal relaxation time. Given that the thermal relaxation time of most tattoo ink particles is less than ten nanoseconds, lasers with very short pulse durations are implemented in tattoo removal. A laser's spot size refers to the cross-section of the laser beam.

Smaller spot sizes produce relatively more scattering in the tissue whereas larger spot sizes produce relatively less scattering. Scattering causes a decrease in the depth of tissue penetration. This plays a role in patients with darker skin tones, as the greater pigmentation there is, the more scattering that results and a lesser depth of penetration is accomplished [25]. Tattoo ink particles are destroyed by the photoacoustic effect. After tattoo ink particles absorb the laser's energy, they expand and produce acoustic waves. These acoustic waves propagate to adjacent tissues, thereby releasing the tattoo pigments from their lysosomes into the

extracellular space. These fragmented pigment particles are phagocytosed, drained via lymphatics, and removed by trans-epidermal elimination [10, 14].

General approach

Patients may desire removal of their tattoo for a plethora of reasons, including but not limited to disliking its appearance, experience regret, and societal factors such as wanting to alter careers. First and foremost, it is important that the dermatologist be sensitive when approaching a patient who desires tattoo removal, as their origins may expand beyond simple dissatisfaction with their appearance. For example, many victims subjugated to human trafficking, especially sex trafficking, are branded by tattoo markings [26, 27]. Formerly incarcerated and gang-involved individuals may want removal of their tattoos to disengage from gang membership, reintegrate into society, obtain employment, and develop positive relationships [5]. Ultimately, for some patients, broaching the topic and undergoing removal may be a sensitive process and dermatologists should remain cognizant of this possibility.

Prior to engaging in laser tattoo removal, a detailed patient history should be elicited. Factors such as a prior history of scarring and poor wound healing, a history of infectious disease, and medication use such as recent isotretinoin use or topical retinol use on the tattoo site or history of gold salt ingestion may alter results [28]. Patients should also be educated on the risks of the procedure, such as the potential for dyspigmentation, scarring, paradoxical darkening, and blistering of the skin. It is also necessary to discuss the importance of sun avoidance and sunscreen protection, as exposure to sunlight during the healing process may result in dyspigmentation. They should also be made aware that the laser tattoo removal process may take multiple sessions, and this is dependent on the size of the tattoo, its age, the amount and type of color present, how the tattoo was performed, location of the tattoo, and if there are multiple layers present.

Given that laser procedures are painful, anesthesia is necessary to promote a comfortable treatment experience. The area to be treated should be prepped with chlorhexidine or alcohol prior to the treatment; in the case of alcohol prep, it should dry completely as it is flammable. It is recommended to perform a test spot prior to the full-length procedure to assess for the development of dyspigmentation and efficacy. Upon application of the laser, immediate whitening is desired, the result of lysosome cavitation; this occurs with both picosecond and quality-switched (QS) lasers. Pinpoint bleeding may also occur. Ideally, it is desired that this immediate whitening occur with the lowest possible fluence so as to not cause damage to the surrounding epidermis. To promote wound healing and appropriate pigment clearance,

patients should wait a minimum of 1 month in between each laser tattoo removal session.

Laser selection

There are multiple factors that should be considered when choosing the appropriate laser for tattoo removal. The type of tattoo, such as whether it is traumatic, cosmetic, performed by a professional or amateur, the patient's Fitzpatrick skin type, and the presence of one or more colors and/or black pigments are some of the factors that need to be accounted for. Physicians should determine whether the tattoo is traumatic, as the presence of combustible materials may cause micro-explosions upon laser treatment and result in scar tissue [12]. Professional tattoos, as compared to amateur tattoos, require more sessions for removal. If a tattoo is composed of multiple colors, different wavelengths may need to be utilized for adequate removal (Table 1) [28]. Also, tattoos that are older in age may require less sessions, as some of the tattoo ink particles may have been physiologically removed by the patient's body. Tattoo ink pigments may also disintegrate secondary to ultraviolet UV radiation exposure, thus over time and exposure to UV light, tattoos may gradually fade without any laser treatment [29, 30]. Patients with darker skin tones, such as Fitzpatrick skin types IV to VI, can be treated with low fluences and larger spot sizes. Conversely, patients with Fitzpatrick skin types I to III can be treated with higher fluences and lower spot sizes. Increased skin pigmentation results in decreases the depth of laser light penetration [31]. QS lasers, including the QS neodymium-doped yttrium aluminum garnet (Nd:YAG), QS Ruby, QS KTP, and QS Alexandrite, have historically been the mainstay in laser tattoo removal [32]. However, the picosecond laser is rapidly becoming the laser of choice in tattoo removal. When utilizing lasers with shorter wavelengths, care must be taken as permanent dyspigmentation may result [14].

Table 1 Tattoo pigment colors and associated absorption wavelengths

Tattoo pigment color	Absorption wavelength (nm)
White	10,600*
Black	694, 755, 1,064
Blue	694, 755, 1,064
Green	694, 755
Purple	694, 755
Red, orange, yellow	532

*The CO₂ laser (10,600 nm) is suggested for removal of white pigments. However, the fractional ablative mode should be used

Tattoos with brown, dark blue, green, and black pigment are generally easier to remove than those that contain orange, yellow, red, and light blue pigment. In dark blue- and black-colored tattoos, patients with Fitzpatrick skin types I to III can be effectively treated with both Q-switched and picosecond lasers of 694, 755, and 1064 nm [14]. Patients with Fitzpatrick skin types IV–VI should be treated with a longer wavelength laser so as to not target melanin, which can result in dyspigmentation of the skin. QS or picosecond lasers of 1064 nm can be successfully used in this population when removing dark blue and black tattoos [12]. Recommendations are varied for the removal of patients with green-colored tattoos—some advise the Alexandrite (755 nm) laser, while others the QS Ruby (694 nm) [12, 14]. Nd:YAG lasers, both QS and PS, have been shown to be less effective in their removal [33]. The removal of red-colored tattoos poses a challenge: some red tattoo pigments may contain toxic metals and increase an individual's risk of allergic contact dermatitis and lichenoid reactions [34, 35]. QS lasers have been reported to cause allergic reactions in patients removing red-colored tattoos, which are thought to be secondary to an immune response triggered by ink dispersal [36, 37]. Recently, hypersensitivity reactions have been reported after treatment of red-colored tattoos treated with the picosecond laser [38]. In patients receiving removal of red-pigmented tattoos with QS or picosecond lasers, it is prudent to administer anti-histamines or corticosteroids prior to the start of the procedure [14]. Ablative lasers may be used to remove red pigment and there is evidence that shows better clearance when ablative lasers are combined with QS lasers, as opposed to ablative lasers alone. However, ablative lasers may cause temporary hypopigmentation and scarring [39]. If using an ablative laser in the removal of tattoos, the fractional ablative mode should be used as the laser energy is able to reach the tattoo pigments but does not produce scars.

Smaller spot sizes produce relatively more scattering, whereas larger spot sizes produce relatively less scattering.

The use of larger spot sizes results in part of the scattered light falling beneath the laser beam, contributing to a downward spread of the laser beam. In contrast, a small spot size results in lateral displacement of the scattering which is lost to downward action.

The Kirby-Desai scale was created to provide patients with a numerical estimate of required treatments for the complete removal of their tattoo (Table 2) [40]. A retrospective chart review study was performed to develop the Kirby-Desai score ($N=100$), taking into account a patient's Fitzpatrick skin type, the location of their tattoo, the color(s) of their tattoo, the amount of ink present as determined by whether the tattoo was completed by a professional or done by an amateur, the presence of scarring and tissue change, and the layering of tattoos, such as when a patient “covers-up” a previous tattoo with a second one. According to this scale, the number of cumulative points correlates with an estimate of the number of treatment sessions required for tattoo removal [40]. For example, a patient with Fitzpatrick skin type II (2 points) who desires the removal of an amateur (1 point), black-colored tattoo (1 point) on their foot (5 points) without any layering (0 points) or scarring (0 points) would require approximately 9 laser removal sessions according to the Kirby-Desai scale. Kirby et al. found that their proposed scale demonstrated a positive correlation with the number of laser removal treatments ($r=0.757$, $P<0.0001$). However, this study has several limitations—Kirby et al. assumed that practitioners utilized a quality-switched Nd:YAG or Alexandrite laser and that sessions were separated by an interval of 6 to 8 weeks. [40] Also, the patient population studied may not have had difficult-to-treat tattoos, such as those with scarring or layered pigment, potentially influencing their results in their creation of the Kirby-Desai scale. [40] Thus, caution should be taken when utilizing this scale as larger, more diverse studies need to be undertaken to assess its reproducibility.

Table 2 The Kirby-Desai scale for treatment number estimation

Fitzpatrick skin type	Location	Amount of ink	Layering	Scarring and tissue changes	Colors
I – 1 point	Head/neck/face – 1 point	Amateur – 1 point	None – 0 points	No scar – 0 points	Black only – 1 point
II – 2 points	Upper trunk/shoulder – 2 points	Minimal – 2 points	Layering – 2 points	Minimal – 1 point	Mostly black with some red – 2 points
III – 3 points	Lower trunk/upper leg – 3 points	Moderate – 3 points		Moderate – 3 points	Mostly black with red and some other colors – 3 points
IV – 4 points	Proximal extremity – 4 points	Significant – 4 points		Significant – 5 points	Multiple colors – 4 points
V – 5 points	Distal extremity – 5 points				
VI – 6 points					

Adverse effects of laser tattoo removal

There exists a myriad of complications and adverse effects that may arise after laser tattoo removal. They can be subdivided into immediate and delayed complications. Immediate complications include the development of blisters, crusting, pain, and pinpoint hemorrhages. Patients should be educated on these potential immediate effects and provide expectant management. Pain and edema after tattoo removal can be alleviated by the usage of ice and minimized by the application of anesthetic cream prior to the procedure. If crusts occur, patients should be advised to not pick at the treatment site as excoriations may introduce infection and cause pigmentary changes. Laser tattoo removal may also produce dyspigmentation, either hypopigmentation or hyperpigmentation. This may be prominent in patients of darker skin color. Also, if the tattoo contains red or yellow pigment, local allergic reactions may occur and manifest as papules, nodules, or plaques that are pruritic. Other complications include the paradoxical darkening of tattoos, as iron oxide or titanium dioxide can be reduced by laser energy, producing darker pigment.

Future perspectives

Multiple laser types are currently being or have already been tested in clinical trials for the removal of tattoos, including picosecond lasers, multi-wavelength laser therapy, combination therapy, and multi-pass therapy.

Picosecond lasers

Picosecond lasers have a short pulse duration, that of the picosecond range. Given that the thermal relaxation time of tattoo ink particles is typically less than 10 ns, theoretically picosecond lasers should outperform QS lasers in terms of efficacy of tattoo removal [41, 42]. Moreover, lasers with nanosecond pulse durations have historically been the mainstay of laser tattoo removal. However, more recently, picosecond lasers have been compared to nanosecond lasers in terms of efficacy and adverse effects. A recent prospective, split study sought to compare the efficacy and adverse reactions of picosecond and nanosecond lasers in 23 subjects with colored or black tattoos. Although statistically insignificant ($P > 0.05$), picosecond lasers were found to produce increased tattoo clearance as compared to patients treated with nanosecond lasers. In terms of adverse events, subjects experienced less pain ($P < 0.001$), blistering, pruritis, and sensation of burning with the picosecond laser as compared to the nanosecond laser. Both lasers produced hyperpigmentation, but picosecond lasers did not

induce hypopigmentation of the skin in this particular study [43]. Alabdulrazzaq et al. found that treatment with a frequency-doubled Nd:YAG 532-nm picosecond laser resulted in hypopigmentation [44].

Other studies have also shown picosecond lasers to be more efficacious than nanosecond lasers in terms of tattoo removal [45, 46]. However, picosecond lasers are also prone to producing dyspigmentation in patients, which is undesirable [45–47]. Also, some studies have not found differences in tattoo clearance efficacy between picosecond and nanosecond lasers [48].

Multi-wavelength lasers and combination therapy

The QS Nd:YAG was the second laser commercially available for tattoo removal, and this laser emits lights at two wavelengths: 532 nm and 1064 nm [15]. Doubling the frequency of the light produced from the 1064 nm Nd:YAG emits light at 532 nm. The 1064 nm Nd:YAG is used to remove tattoos with blue or black pigment, whereas the 532 nm Nd:YAG is used to remove tattoos with red pigment [15]. Studies have shown that the 532 nm Nd:YAG is superior to the QS ruby and QS 1064 nm Nd:YAG in removing tattoos with red pigment [49]. Nd:YAG has also been combined with other therapies in an attempt to improve pigment removal. Some studies have showed that ablative and non-ablative fractional resurfacing combined with QS laser therapy increases pigment clearance and reduces peri- and post-procedure adverse effects, such as blistering and hypopigmentation [50].

Multi-pass therapy—R20 and R0

Multi-pass therapy using the R20 or R0 method may be used to reduce the number of sessions needed for tattoo removal. The R20 method calls for using a laser four times in one session, with passes at 20 min intervals, which may allow treatment of progressively deeper layers of the dermis [51]. In the R0 method, tattoos are treated with 3 passes and topical perfluorodecalin, used to reduce the whitening reaction, is applied after each pass [52]. These two methods have been reported to achieve greater pigment clearance than single-pass treatments [51, 52]. The FracTat technique uses QS Nd:YAG (1064 nm) fractional ablative micro-drilling at the initiation of treatment to rapidly clear the frosting effect—this allows for faster execution of multiple passes than the R20 method [53].

Conclusion

Laser therapy is currently the mainstay of treatment in the removal of tattoos. Lasers are more efficacious than other removal types, such as salabrasion, dermabrasion, and

electrocauterization. Dermatologists should be well-versed in laser physics and terminology as well as understand the rationale behind choosing the appropriate laser type. QS lasers are the most commonly used with the greatest amount of evidence; however, other laser types, such as the picosecond laser, and updated methodology, such as the implementation of multi-wavelength lasers, combination therapy, and multi-pass therapy, are gaining prominence in the realm of laser tattoo removal.

Declarations

Conflict of interest The authors declare no competing interests.

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