OPTIMIZATION OF LASER RADIATION PARAMETERS FOR REMOVING TATTOOS AND PERMANENT MAKEUP OF VARIOUS PIGMENT COMPOSITIONS

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ABSTRACT

This article presents an overview of modern approaches to optimizing laser parameters for tattoo and permanent makeup removal with various pigment compositions. It examines the mechanisms of laser-pigment interaction, the influence of color, composition, and depth on treatment effectiveness, and key laser parameters: wavelength, energy, pulse duration, spot size, and session frequency. The characteristics of difficult-to-remove pigments, such as white pigments and those containing TiO_2*, are discussed, along with recommendations for safe and effective customized treatments.*

The scientific innovation lies in the generalization and comparison of laser exposure parameters with the chemical composition and physical properties of tattoo and permanent makeup pigments, which allows for the rational optimization of the choice of wavelength and radiation modes to improve the efficiency and safety of removing complex pigments.

The popularity of tattoos and permanent makeup (PMU) has increased dramatically in recent decades, leading to increased demand for safe and effective removal. Laser therapy remains the gold standard for removing both decorative tattoos and PMU due to the selective interaction of laser light with pigmented particles while sparing surrounding tissue.

The mechanism of action of modern short-pulse and ultra-short-pulse (nanosecond and picosecond) lasers is based primarily on photoacoustic /photomechanical fragmentation of pigment particles, followed by fragment removal by macrophage cells and the lymphatic system. Short pulses reduce thermal damage to adjacent tissues and increase the efficiency of fragmentation of particles of varying dimensions [1].

Despite advances in technology, the clinical efficacy and safety of procedures vary greatly and depend on numerous factors. Key factors include the spectral and chemical composition of the pigment (color, organic/inorganic components, presence of metal oxides, such as TiO2), the depth and density of pigment injection, the patient's skin phototype, and the selected laser parameters (wavelength, fluence, pulse duration, spot size, cooling modes, and intervals between sessions). Variability in pigment composition and its interaction with different wavelengths are a common cause of uneven efficacy, late effects (paradoxical darkening), and complications [2].

Permanent makeup removal presents a particular clinical challenge: PMU pigments are often complex mixtures of dyes, are injected more superficially, form fine lines, and are used in areas with thin skin (eyelids, eyebrows, lips). These characteristics require different tactics and increased caution when selecting removal parameters compared to traditional tattoos. Furthermore, the literature notes an increase in reports of allergic and inflammatory reactions specific to PMU, which also influences the choice of removal strategy [3].

A separate and well-documented obstacle is the presence of titanium (TiO_2) and some inorganic pigments in inks, which can cause "paradoxical darkening" or reduce the response to traditional wavelengths. Clinical and histological studies show a correlation between TiO_2 content and poor treatment response, and also reveal cases of pigment darkening after treatment with certain wavelengths. This circumstance emphasizes the need for ink composition analysis and careful selection of laser treatment modes [4].

Technological innovations, primarily the introduction of picosecond systems and combined approaches (e.g., sequential application of different wavelengths or a combination of picosecond exposure with fractional techniques), demonstrate improved clinical results for a range of difficult-to-treat colors (blue, green, dark shades), although the evidence base is still evolving and requires standardization of protocols. Clinical comparisons of picosecond and nanosecond systems show advantages in the number of sessions and quality of clearance in some groups, but the results between studies are not entirely consistent [5].

The purpose of this article is to analyze the available data on the influence of pigment composition on the response to laser tattoo removal and PMU and to develop practical principles for optimizing laser radiation parameters (wavelength, fluence, pulse duration, spot size, intervals between sessions, etc.) taking into account the risks and limitations of current research.

The physical basis of laser removal of tattoos and permanent makeup is selective Photothermolysis , which involves the selective absorption of energy by the pigment with minimal damage to surrounding tissue. When exposed to a short-pulse laser, the pigment heats up faster than it can transfer heat to the tissue, causing a photoacoustic (photomechanical) effect-the explosive destruction of particles into smaller fragments, which are then available for subsequent absorption by macrophages and transport by the lymphatic system [6].

To effectively destroy pigment, the pulse duration must be shorter than the thermal relaxation time of the particles; this eliminates thermal damage to surrounding skin structures:

- nanosecond Q- switched Nd:YAG and ruby lasers provide photothermolysis with a partial mechanical effect;
- picosecond systems create a more pronounced photoacoustic burst, which improves the fragmentation of persistent pigments and reduces the risk of side effects.

Comparative clinical data demonstrate faster clearance with picosecond therapy [7].

Each pigment has an individual absorption spectrum, which determines the required wavelength for its destruction:

Table 1 - Dependence of pigment removal efficiency on laser wavelength

Pigment color	**Recommended wavelength**	**Reason for choice**	**Clinical features**
Black, dark blue	1064 nm (Nd:YAG	Maximum	Most easily removed ;

	QS)	absorption by melanin and carbon particles; deep penetration	minimal risk of burning for darker phototypes
Red, orange	532 nm (Nd:YAG QS, green line)	Strong absorption of iron oxide and organic dyes	Heat-induced color changes may occur ; caution is advised
Blue, turquoise, yellow-green	755 nm (pico-Alexandrite) or 694 nm (Ruby)	Better absorption by copper/cobalt chromophores	Often require a multi-wave approach
Yellow	532 nm / 755 nm (limited effectiveness)	The absorption spectrum is weak	Slow removal, high resistance
White (TiO_2)	Non-target spectrum for standard wavelengths	TiO_2 reflects light; upon heating, reduction → darkening is possible	High risk of "paradoxical" darkening
Brown (PMU-lips, eyebrows)	1064 nm (first choice) → 532 nm if needed	Mixed compositions (usually Fe_2O_3 + organics)	Risk of turning into a dark shade
Violet	Combined approach: 532 nm + 755/694 nm	Complex absorption spectrum	Often requires adaptive protocols

Removal is difficult when using inorganic metal oxides, especially:

1. TiO2 (white) reflects the beam and may darken after laser
2. Iron oxide ink (red/brown) may turn black FeO heated by picosecond and 532 nm radiation.

The latest toxicological assessment of tattoo pigments shows complex chemical reactions during their breakdown [8].

The destroyed pigment is absorbed by macrophages, transported by the lymphatic system, and gradually eliminated from the body. Multiple sessions are required, with intervals of 6–12 weeks improving clearance. Slower clearance may be observed in patients with low immune activity, deep pigment deposits, and high tattoo density [9].

The effectiveness of laser tattoo and permanent makeup removal is largely determined by the chemical composition of the pigment, its color, particle structure, and depth of penetration into the skin. Even pigments of the same shade can differ in their absorption spectrum, resulting in different responses to laser radiation.

Pigments are conventionally divided into organic and inorganic, presented in more detail in Table 2.

Table 2 - Organic and inorganic components of pigments

Type	Examples	Peculiarities	Impact on removal
Organic dyes	Aniline, azo dyes	Good laser absorption	More easily fragmented
Inorganic metal oxides	TiO_2 , Fe_2O_3 , Cu-phthalocyanine	Thermally stable	Darkening may occur, low efficiency

One of the determining factors for the success of laser removal is the depth of pigment placement and the particle size distribution of the ink. In decorative tattoos, the pigment is typically injected into the deep layers of the dermis—up to 1.5–2 mm deep—and has larger particles and a higher distribution density. This increases the pigment's resistance to laser exposure and requires the use of long-wavelength systems with high penetrating power (e.g., 1064 nm) to achieve a therapeutic effect.

In contrast, permanent makeup injections are applied much more superficially, into the upper layers of the dermis, which should theoretically facilitate removal. However, PMU pigments are characterized by a smaller particle size and a more complex chemical structure, which can lead to unpredictable behavior under laser treatment.

Particle size is important when choosing pulse duration: the larger the particle, the more energy is required for its fragmentation. Effective destruction of large aggregates requires the dominance of the photoacoustic mechanism, which is achieved with ultra-short pulse durations in the picosecond range. Clinical and experimental studies confirm that picosecond lasers provide more pronounced particle fragmentation and, consequently, accelerated pigment removal compared to nanosecond systems [10].

Pigments used for permanent makeup vary widely in composition, as they are designed to create natural skin, hair, and lip tones. The most common components of these inks are iron oxides (Fe_2O_3), which create a reddish-brown color palette, and titanium dioxide (TiO_2), which is used as a white corrective pigment. Unlike organic azo dyes, these inorganic compounds have high thermal stability and a low absorption coefficient at standard wavelengths, which reduces the effectiveness of laser photodestruction.

Particular attention should be paid to the risk of paradoxical darkening—a process in which red and flesh-colored iron-containing pigments are reduced to the black form FeO under laser exposure . This complication significantly complicates further removal and requires revision of the exposure parameters [11].

An additional factor complicating PMU removal is the high application density in sensitive anatomical areas (eyelids, lips, eyebrows), where the skin is thinner and the risk of scarring is higher. Modern spectral studies, including hyperspectral imaging, show that PMU pigments often have a mixed absorption spectrum, making the target wavelength difficult to determine and requiring flexible, individualized removal strategies [12].

Thus, permanent makeup is characterized by a combination of superficial placement and chemical resistance of the pigment, which makes its removal no less, and often more difficult, than the removal of classic decorative tattoos.

Table 3 - Effect of pigment composition on the efficiency and risks of removal

Pigment	Main component	Reaction to laser	Possible complications	Optimal approaches

Black (universal)	Carbon	Good response at 1064 nm	Low	Picosecond Nd:YAG
Blue /green	Cu-phthalocyanine	Moderate effectiveness	Combined wavelengths are required	755 nm / 694 nm + multiple sessions
Red/brown PMU	Fe_2O_3	Risk of darkening	Transformation to black FeO	First 1064 nm → carefully 532 nm
Yellow	Organic azo dyes + TiO_2	Weak absorption	Resistance to removal	Pico technology, low fluence
White (corrector)	TiO_2	Reflects the beam	Darkening to blue /gray	Very careful protocol, test pulse
Eye/lip pigments	Mixed composition	Unstable behavior	Development of inflammation	Customization

Therefore, analysis of current data shows that the chemical composition and physical characteristics of pigments are crucial factors in the success of laser removal. Tattoo and permanent makeup pigments vary in their depth, particle size, and optical properties, which directly impacts their sensitivity to the choice of wavelength and laser pulse duration. Inorganic compounds, including iron oxides and titanium dioxide, are the most challenging to remove, as they have low light absorption and are prone to undesirable chemical transformations, such as paradoxical darkening. Furthermore, permanent makeup pigments often have a mixed composition, requiring individualized parameter selection and increasing the risk of complications. Picosecond lasers demonstrate the best efficacy when working with large and stable particles, providing a pronounced photoacoustic effect and safer clinical outcomes.

The effectiveness of laser tattoo removal is determined by a combination of radiation parameters, including wavelength, pulse duration, energy density (fluence), pulse repetition rate, and spot size. Optimizing each of these factors improves photoselectivity and reduces the risk of damage to surrounding tissue.

The main principle of laser removal is selective Photothermolysis, according to which the wavelength should match the pigment's absorption spectrum as closely as possible, while the penetration depth should be sufficient to reach dermal deposits. Carbon black pigments absorb radiation most effectively in the 1064 nm range (Nd:YAG), while red and orange pigments are best removed at 532 nm , and blue and green pigments require 694 nm (ruby laser) or 755 nm (alexandrite laser).

Pulse duration is a critical parameter and must match the thermal relaxation time of the pigment particle. Picosecond lasers are more effective than nanosecond systems due to the dominant photoacoustic disruption of particles, which ensures more pronounced pigment fragmentation and a reduced number of treatments. However, it is important to avoid excessive energy, which can cause scarring and inflammatory changes in the skin.

Spot size and fluence also affect the penetration depth and uniformity of energy distribution in the dermis. A larger spot (4–8 mm) increases the depth of light energy delivery and promotes better dispersion of absorbed photons, while too small a diameter can lead to superficial overheating. Optimal settings are individually selected based on skin phototype , pigment color, and application density. This requires clinical experience and step-by-step parameter testing, especially when working with difficult pigments such as Fe_2O_3 and TiO_2.

Thus, successful optimization of laser parameters requires a balance between maximizing selective pigment destruction and minimizing thermal damage to the skin. Precise adjustment of laser treatment modes is essential for safe and predictable clinical results.

Optimizing tattoo and permanent makeup removal technologies must consider not only the physical properties of laser radiation but also the individual characteristics of the patient and pigment compositions. Clinical experience and modern research allow us to identify a number of principles aimed at improving the effectiveness and safety of procedures. First and foremost, it is recommended to conduct a preliminary diagnosis of the pigment's composition and optical characteristics using dermatoscopy, spectral analysis, or test pulses. This is especially important when working with red and flesh-colored pigments containing Fe_2O_3 and TiO_2, which are prone to paradoxical darkening.

For deep and intense dark tattoos, the optimal choice is to use a picosecond An Nd:YAG laser (1064 nm) provides high penetrating power and a pronounced photoacoustic effect. When removing colored pigments, it is recommended to combine wavelengths, selecting the absorption range characteristic of each shade, while adjusting the fluence and spot size to minimize epidermal overheating.

Particular attention should be paid to patients with dark skin (phototypes III–VI): to prevent post-inflammatory hyperpigmentation, it is necessary to reduce fluence , increase intervals between treatments, and apply skin cooling before, during, and after laser treatment. It is also recommended to avoid traumatic techniques until pigment removal is complete and maintain strict photoprotection throughout the treatment course.

An additional factor for success is an adequate interval between sessions: too frequent treatments lead to accumulation of thermal damage, while an optimal waiting time (6–8 weeks) ensures gradual tissue cleansing by macrophages and reduces the risk of scarring.
Thus, practical recommendations boil down to individualizing laser exposure parameters, strict safety control, and monitoring the dynamics of removal with possible adjustments to strategies when working with resistant pigments.

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