Lasers for the Treatment of Pigmented Lesions

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Various laser and light systems have been developed specifically for the treatment of pigmented skin lesions. These lesions include both the exogenous pigment of tattoo particles (both professional and amateur) and the endogenous pigment of melanin in nevi and other pigmented lesions. Endogenous pigment is of 2 different types: eumelanin and pheomelanin.

Eumelanin is a dark-brown to black pigment molecule that absorbs light broadly across UV, visible, and near-infrared wavelengths. In most individuals, eumelanin is the primary product of the melanin biosynthesis pathway, present in far greater quantities than is the copper-red alternative product pheomelanin. Both pigment types are produced and packaged into melanosomes within melanocytes, yet the greatest concentrations of melanin can be found within the cytoplasm of neighboring cells such as basal keratinocytes and follicular matrix cells. The size, density, and distribution of melanosomes within these cell types largely determine overall skin and hair color. Focally aberrant concentrations of melanocytes and melanosomes in the epidermis and/or dermis can produce a wide range of pigmented lesions and anomalies.

Targeting Melanosomes

Melanosomes are melanin-containing organelles that range in size from 0.5 to 1.0 µm. They comprise the primary skin target of laser and light treatment of endogenous pigment. Melanin has an absorption spectrum that ranges from UV to near-infrared, which lends itself to possible treatment with a wide variety of lasers. Selection of treatment wavelength is based largely on avoidance of the absorption peaks of other chromophores. When the fluence threshold for melanosome disruption is reached, the pigmented cell dies.

Because melanin is packaged into 0.5- to 1-µm–sized melanosomes, pulse durations of less than 1 microsecond are needed to achieve thermal confinement within these subcellular structures. Based on the theoretical thermal relaxation time, the optimal pulse duration is 70 to 250 nanoseconds. Therefore, Q-switched lasers are excellent for targeting melanosomes. Nanosecond-pulsed lasers (eg, Q-switched ruby, alexandrite, Nd:YAG) operate under these conditions, rapidly heating melanosomes to temperatures high enough to induce cavitation and rupture.

Melanin absorbs DNA-damaging UV radiation, with absorption dropping precipitously as wavelengths increase toward the infrared range. Although the absorption spectra of melanin and oxyhemoglobin overlap, preferential absorption by melanin occurs between approximately 600 and 1200 nm, providing a useful window for selective photothermolysis of melanin-laden targets. Most melanin-targeting lasers, including the Q-switched ruby, alexandrite, and Nd:YAG lasers, operate in this area and are capable of reaching dermal melanin at various depths. Although shorter-wavelength lasers such as the 510-nm copper bromide cannot penetrate deeply enough into the dermis to treat dermal melanocytic processes, they are still highly effective in treating epidermal pigmented lesions such as lentigines. By contrast, longer-wavelength lasers such as the 1064-nm Nd:YAG can penetrate deeply into the dermis but must operate at far greater fluences to achieve clinically significant target effects because of relatively low melanin absorption.

Selective Photothermolysis of Melanin

Under electron microscopy, the process of selective photothermolysis of melanosomes has been visualized. The process begins with the formation of central zones of lucency within the melanosomes followed by melanosomal membrane rupture. This latter event occurs at a threshold fluence and correlates with the clinical appearance of immediate epidermal whitening—a transient phenomenon that also occurs during short-pulsed laser treatment of tattoos and is most likely caused by the sudden release of water vapor and nitrogen gas as the subcellular particles undergo phase change, cavitation, and rupture.

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Paradoxically, subthreshold fluences appear to enhance melanin production by unknown mechanisms. In contrast, suprathreshold fluences cause blebbing and rupture of melanosome membranes followed by damage to adjacent cellular structures such as the nucleus and hemidesmosomes. These latter changes, which reflect both photothermal and photomechanical laser effects, correlate with the light microscopic findings of subepidermal blistering and ring-cell formation. Ring cells represent damaged basal keratinocytes and melanocytes that contain peripherally dispersed melanin and nuclear debris. Animal models have demonstrated that shorter-wavelength lasers such as the 355-nm Q-switched Nd:YAG are capable of inducing ring-cell formation followed by only transient epidermal hyperpigmentation. By contrast, longer-wavelength Q-switched Nd:YAG pulses can induce permanent hypopigmentation (532 and 1064 nm) and leukotrichia (1064 nm) at suprathreshold fluences, probably because they deliver "lethal" energy to melanocyte reservoirs in the epidermal rete, follicular units, and appendegeal structures.

Tattoos treated with short-pulsed lasers yield fragmentation of the ink particles and selective death of pigment-containing cells, with resultant pigment release. There are several speculated mechanisms for removal of the pigment particles. Some ink is lost in an epidermal crust, some in the lymphatics, and some is rephagocytosed by dermal cells. Different lasers are required to manage different pigments. Q-switched ruby lasers can be used at fluences of up to approximately 10 J/cm^2 and emit a 694-nm deep red light that is well absorbed by melanin. At a 20- to 40-nanosecond pulse duration, this laser can also effectively treat most tattoo colors except red. Q-switched ruby lasers are particularly useful in the treatment of deep pigmented lesions such as nevi of Ota. The literature also contains multiple reports of the successful use of the ruby laser for the treatment of solar lentigines, ephelides, and blue or other melanocytic nevi.

The Q-switched Nd:YAG laser emits energy in the near-infrared range at 1064 nm, with typical pulse durations of 10 nanoseconds. Its primary use is in the treatment of dermal pigment such as a nevus of Ota and removal of black tattoo pigment. The 1064-nm energy can be frequency doubled to produce 532-nm visible green light by passing it through a potassium titanyl phosphate crystal. This frequency-doubled Nd:YAG laser can effectively remove epidermal melanin pigment and red tattoo ink but not green ink. Complications include hypopigmentation or hyperpigmentation and transient textural changes at higher fluences.

Suggested Reading

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