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Assessment of actual laser emission at 532nm in tattoo removal devices

Avaliação da emissão real de laser em 532nm nos equipamentos para remoção de pigmentos

Original Article

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ABSTRACT
Introduction: The use of potassium titanyl phosphate (KTP) crystals for second-harmonic generation of 532nm waves from a 1064nm source is presented as a more efficient method for removing residual tattoo pigments with lasers. It is crucial to measure the actual performance of the available technologies on the market, which has not been done to date.
Objective: To assess the performance of laser systems available on the Brazilian market by measuring the amount of energy from the fundamental wavelength (1064nm) that is effectively converted to 532nm.
Methods: The 532nm wavelength was measured on Etherea MX, Spectra XT, Inkie, Ladybug and Deltalight equipment using the metrological standard of the National Institute of Metrology of China, model NIM-1000 Results: The results were unsatisfactory for most of the analyzed systems.
Conclusions: The findings suggest potential photonic design flaws in the equipment and methodological deficiencies in the conformity assessment by product certification bodies, compromising the desired clinical outcomes.
Keywords: Lasers; Solid-State; Coloring Agents; Tattoo Removal; Lasers, Dye.

RESUMO
Introdução: *O uso da geração de segunda harmônica da banda em 1064nm pelos cristais de KTP, originando o feixe em 532nm, é apresentado como uma forma mais eficiente para a remoção de pigmentos residuais de tatuagem, sendo essencial mensurarmos a real entrega das tecnologias disponíveis no mercado, algo não disponível até a presente data.*
Objetivo: *Avaliar os dispositivos disponíveis no mercado brasileiro para mensurar o quanto do comprimento de onda fundamental, em termos de energia, é efetivamente convertido em 532nm.*
Métodos: *Realizado a mensuração do comprimento de onda de 532nm nos equipamentos Etherea MX, Spectra XT, Inkie, Ladybug e Deltalight através do padrão metrológico do National Institute of Metrology da China, modelo NIM-1000*
Resultados: *Notam-se resultados insatisfatórios para a maioria dos equipamentos analisados.*
Conclusões: *Os resultados indicam possível falha de design fotônico dos equipamentos e falha metodológica para avaliação de conformidade pelos organismos certificadores de produtos, comprometendo o resultado clínico almejado.*
Palavras-chave: *Lasers de Estado Sólido; Corantes; Remoção de Tatuagem; Lasers de Corante.*

INTRODUCTION

The practice of tattooing has been part of human culture since the beginning of civilization. The first descriptions of tattoos date back to 2000 B.C. on Egyptian mummies.[1] Over time, the methods of application and the use of various colored pigments have evolved, allowing for more complex tattoos.[2] Removal attempts are also ancient, with the first techniques dating back to 543 B.C., developed by the Greeks, who practiced abrasion followed by the application of inorganic salts.[1] Currently, quality-switched (Q-switched) lasers are most commonly used in permanent makeup and tattoo removal.[3] Q-switching refers to the mechanism used to control the temporal profile of the laser output, that is, it allows high-energy nanosecond pulses to be generated. These lasers gained popularity in the 1990s, when different studies demonstrated their effectiveness in reaching the pigments located in the dermis, such as tattoo ink.[4]

Three types of Q-switched lasers with pulse widths on the order of nanoseconds to microseconds are used for tattoo removal, but they vary in wavelengths: the ruby laser (694nm), the alexandrite laser (755nm), and the Nd:YAG laser (532nm in the second harmonic, 1064nm in the fundamental mode).[3] The Q-switched ruby and alexandrite lasers are used to remove black, blue, and green pigments. The Q-switched 532nm Nd:YAG laser is used for the removal of red pigments and the 1064nm Nd:-YAG laser is used for removal of black and blue pigments.[5] Variations in the chemical composition and absorption spectrum of pigments make it a challenge to foresee the pigment reaction to a chosen laser wavelength.[6] Colors such as yellow and orange are known to be very resistant, and colors such as red and green have a highly variable response.[1] Reddish pigments are usually resistant to 532nm laser treatment due to the Purkinje effect, in which mesopic conditions give way to photopic effects. Under these conditions, the cones in the retina, which are responsible for the perception of color, are much more sensitive to light at wavelengths close to the absorption maximum of rhodopsin and that of the other opsins in the cones, meaning the average normal human eye is most sensitive at a wavelength of 555nm (green).[7] Thus, even a small amount of green light in a laser beam, such as the green light generated by the second harmonic of a 1064nm laser, can appear very bright to the naked eye when it hits a reflective target. This can create the false impression that that laser beam contains a much higher percentage of green light (532nm, in our example). The Q-switching technique, used in lasers for pigment removal, generates extremely short pulses (in nanoseconds) with high energy (in Joules). When absorbing this high energy, the target chromophore and the structures storing it are fragmented through a selective photothermolytic effect known as photodisruption.[8] Photodisruption is often accompanied by a photoacoustic effect, as rapid light absorption by the target chromophore results in a significant increase in temperature, leading to the formation of plasma and cavitation bubbles. This process is desirable in tattoo removal, as it enhances the breakdown of the pigment.[9] This means the interaction between the laser and the chromophore occurs in such a brief interval that the heat generated does not dissipate efficiently into adjacent tissues, significantly reducing damage to the area surrounding the tattoo.[9] Thus, the laser can specifically act on the target chromophore (pigment) and the cells that store it, preserving the other structures of the integument. Quantitatively, the region subjected to thermal damage by the laser can be determined by the laser pulse duration using the following formula, where D is the thermal penetration depth (cm), k is the thermal diffusivity constant, and t is the time (s).

D = (4kt)1/2 (I)

Experimentally, the thermal diffusivity of biological tissues such as skin has been calculated to be approximately 2.9 (±0.5) x 10-4 cm^2 s-1.[10]

To illustrate the impact of pulse duration on thermal penetration in tissue, consider a typical pulse from a laser hair removal device, which has a duration of 30ms. Under optimal conditions, when the laser pulse hits the target chromophore and is not absorbed by surrounding structures, it will increase the temperature until thermal equilibrium is reached at a depth of approximately 0.06mm (60μm, corresponding to the size of approximately 3 to 7 epithelial cells). In contrast, a typical Q-switched laser pulse, which has a duration of only 10ns, will generate a thermal penetration of only 0.034μm, smaller than the dimension of a single cell. However, due to the cavitation process resulting from photodisruption, the cells storing the pigments and other surrounding cells may be mechanically ruptured.[9] Although laser pulse energy and duration are crucial for the success of tattoo removal, another parameter determines which chromophores will be targeted: the wavelength. The preferred laser for pigment removal is the Q-switched Nd:YAG, which emits its most intense light at the 1064nm wavelength in the near--infrared spectrum, thanks to its quasi-three-level system. This wavelength can be absorbed by several pigments of different colors and compositions; however, some residual pigments, particularly red and orange, are resistant to removal with the 1064nm Q-switched Nd:YAG. Therefore, a nonlinear optical material is often used to generate the second harmonic, ie, to double the fundamental frequency of the incident laser. Antireflection-coated potassium titanyl phosphate (KTP) crystals are typically used for this purpose. Antireflection coating, in addition to generating a faint bluish reflection, also produces destructive interferences in the reflected beams, thereby preserving nearby optical structures. KTP allows the generation of a beam that maintains the same temporal profile and transverse electromagnetic mode as the incident beam, but with a wavelength shifted to 532nm in the green visible spectrum.[11] Structurally, most commercial lasers for tattoo removal use removable or adjustable lens sets containing KTP, placed extrinsically in relation to the resonant optical cavity. In this way, the 1064nm laser beam that would hit the operative field is now directly propagated through the KTP crystal to generate the second harmonic. Although some technical specifications of KTP crystals indicate a maximum conversion efficiency of over 80%,[12] in practice, a lower efficiency is observed in second harmonic generation due to several factors that will be discussed in this article, which can complicate or even prevent the removal of some residual pigments.

METHODS

This study assessed the following laser equipment (Table 1): Etherea MX® (Vydence, São Carlos, Brasil), Spectra XT® (Lutronic Goyang-si, South Korea), and Inkie® (Countourline Sete Lagoas, Brasil), all registered with the Brazilian National Health Surveillance Agency (ANVISA). Additionally, Ladybug® (WB Brasil), Delta Light® (Delta), and an unbranded model were included, which lacked ANVISA registration or were manufactured before ®completing registration at the time of testing. The objective was to evaluate the efficiency of second harmonic generation by these devices and their compliance with specific laser metrology requirements. These include the output energy reported on the human-machine interface (HMI) and the actual laser beam energy emitted, as per NBR/IEC 60.601-2.22 standards by the Brazilian National Institute of Metrology, Standardization and Industrial Quality (Instituto Nacional de Metrologia, Qualidade e Tecnologia, INMETRO) for ANVISA registration. The study also investigated whether low efficiency is a specific issue with certain models or a widespread phenomenon.

Measurements were conducted using a NIM-1000 metrology standard from the National Institute of Metrology (NIM) of China, capable of measuring short laser pulse energies from 400 to 2000nm, ranging from 20 to 2700mJ. A photovoltaic sensor with integrated attenuator, responsive to 1064nm at 1.34 x 10-1 J/V and 532nm at 2.02 x 10-1 J/V (manufactured in 2018), was employed. Results were cross-checked against an Molectron EM400 energy meter (USA) using Scintilum (Brazil) photovoltaic sensors with specific diffusers and attenuators for 532nm/1064nm, sensitive to 1064nm at 2.35 x 10-1 J/V and 532nm at 3.15 x 10-1 J/V. A Ranbond VLE-1000 laser energy meter (China, serial number 20220305E1), calibrated by the NIM of China on March 7, 2022, served as a reference. A calibration certificate was issued under code GXjg2022-00399 (Table 2).

Tests were conducted in a controlled laboratory environment with temperature and humidity monitoring. The mean and standard deviation of 10 consecutive pulses were recorded at 2 Hz frequency to measure average energy at 1064nm. Subsequently, another 10 consecutive pulses at the same frequency were performed using the second harmonic generated by each device, and the arithmetic mean and standard deviation values were recorded.

Table 1: Devices analyzed in the study

Device	Brand	Model	ANVISA registration N.	Serial N.
1	Vydence	Etherea MX	80058580021	008642-16
2	Countourline	Inkie	80832470003	895236
3	Countourline	Inkie	80832470003	569823
4	Lutronic	Spectra XT	10343650037	VX121A005
5	Lutronic	Spectra XT	10343650037	VX115C032
6	WB	Ladybug	Not registered	201900306
7	Delta	Delta Light	Not registered	X9B300021011 24
8	Not apparent	J-200	Not registered	AS102820J- 2005962

Source: Unpublished own data

Table 2: Calibration certificate results for the VLE-1000 laser energy meter

λ (nm)	Measurement range	Pulse width (ns)	Reference value	Measured value	Correction factor	Uncertainty (k=2)
1064	3.482J	10	1.140J	1.135J	1.00	Urel = 3%
1064	348.2mJ	10	197.6mJ	198.4mJ	1.00	Urel = 3%
532	351.8mJ	10	237.5mJ	235.3mJ	1.01	Urel = 3%
532	105.5mJ	10	50.19mJ	50.25mJ	1.00	Urel = 3%

Source: Unpublished data extracted from the GXjg2022-00399 calibration certificate issued by NIM on March 7, 2022.

Data on emission at 532nm were collected directly using the energy meters and sensors, employing special filters to assess the spectral composition of laser beams at 532nm, 1064nm, and combined 1064nm + 532nm wavelengths. The filters included were:

- BG38 (Tangsinuo, China): High transmittance in the visible spectrum, high absorbance in the near-infrared spectrum, 50mm in diameter, and 2mm thick.
- HB720 (Tangsinuo, China): Inverse spectrophotometric profile, 50mm in diameter, and 2mm thick.

The transmission spectra of the filters are shown in figures 1 and 2 and were confirmed via T% measurement using a Thermo Scientific Genesys 10S UV-Vis spectrophotometer in scan mode from 400 to 1100nm at 1nm increments.

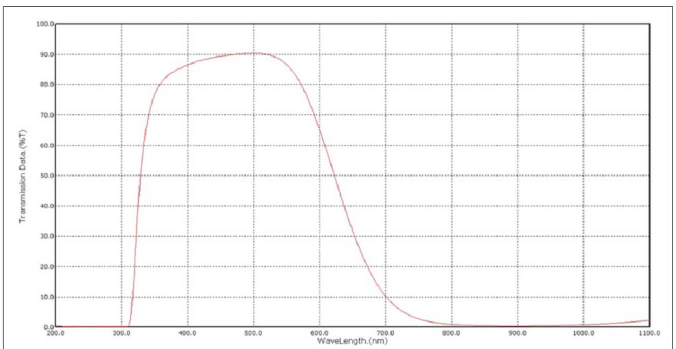
RESULTS

Measurements were conducted between October 3rd and 4th, 2022, at a mean ambient temperature of 22.0±0.5°C and relative humidity of 63.1±3%. The results for each device are summarized in table 3, obtained following the methodology previously outlined and considering a standard deviation (σ) < 0.037.

Most of the tested devices, including those registered with ANVISA, exhibited a conversion efficiency of less than 30% for generating 532nm, a parameter that does not appear to be assessed by INMETRO.

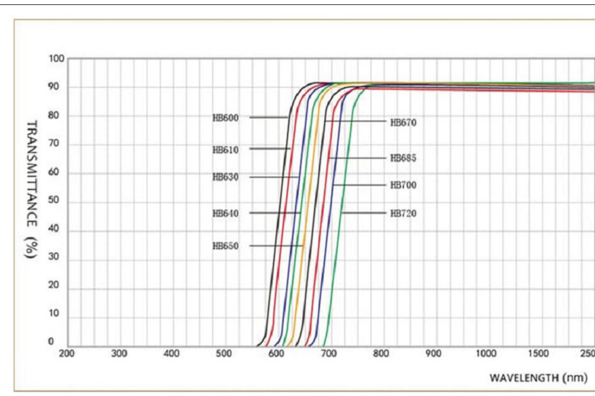
DISCUSSION

There is a common belief that the second harmonic generation of 532nm is high due to the photoacoustic effect in pigmented material. However, in practice, most laser emissions predominantly remain at the fundamental wavelength of 1064nm. In fact, KTP has a conversion efficiency far below the 50% or 80% stated in technical data sheets due to issues such as crystal quality or phase matching problems. This limitation is compounded by the photonic engineering of the laser equipment currently available on the market (with the exception of Lutronic's Spectra), in which KTP crystals are coupled to the laser output window, close to the patient's skin, without the use of additional elements to block the fundamental wavelength of the Q-switched Nd:YAG laser either by reflection (e.g., dichroic mirrors) or by absorption (e.g., traditional optical filters). As a result, the emitted beam typically contains both 1064nm and 532nm wavelengths rather than exclusively 532nm. This combined resultant beam induces a photoacoustic effect on the photographic paper used for laser cavity alignment and beam profile monitoring. Photovoltaic sensors confirm higher readings due to this combined beam, misleadingly suggesting efficient second harmonic generation. This sensory deception is corroborated by the Purkinje effect, where our retina is more sensitive to light in the center of the optical spectrum—precisely in the range of light emerging from the KTP crystal following irradiation by the Nd:YAG laser's most intense band emission (1064nm). Thus, even a small fraction of laser light at 532nm appears intensely bright compared with the fundamental wavelength of the laser, which is in the near-infrared (invisible). Consequently, during testing, laser operators are doubly deceived: first by seeing intense light emerging from the output window, corresponding to a minor conversion by often poorly positioned and low-quality KTP crystals; and second by a notable photoacoustic effect on some pigmented structures caused by unconverted 1064nm laser light also emanating from the KTP crystal without being converted or blocked by a filter.



*Fonte: Especificações técnicas do filtro QB21 ϕ50*1,0 mm comercializado pela Tangsinuo Store, disponível em https://pt.aliexpress.com/item/4000065793459.html e acessado em abril / 2022.*

FIGURE 1: T% spectrum of the Visible Bandpass Filter used in the tests



*Fonte: Especificações técnicas do filtro HB720 ϕ50*2,0 mm comercializado pela Tangsinuo Store, disponível em https://pt.aliexpress.com/item/4000438441353.html?gatewayAdapt=glo2bra e acessado em abril / 2022*

FIGURE 2: T% spectrum of the IR Pass Filter used in the tests (model HB720, represented by the green curve)

TABLE 3: Summary of measured values for each device (mean values)

Device	Adjusted energy (mJ)	Total energy (mJ)	Percent error between adjusted and total energy	Energy at 532nm with filter (mJ)	Conversion rate to 532nm
Etherea MX	600	537	10.5	92.4	17.21
	1200	1115	7.08	175.2	15.71
	1500	1410	6	213.4	15.13
Inkie (1)	112	123.3	10.09	20.01	16.23
	503	566.9	12.7	134.7	23.76
	792	813.5	2.65	187.1	23.00
	1200	1118	6.83	293.9	26.29
Inkie (2)	112	127.8	14.11	34.58	27.06
	503	549.4	9.22	118.7	21.61
	792	817.2	3.18	210.9	25.81
	1200	1210	0.83	328.4	27.14
Spectra XT (1)	52	36.84	29.15	36.63	99.43
	103	74.05	28.11	73.57	99.35
	206	148.1	28.11	147.1	99.32
	387	239.3	38.16	238.4	99.62
Spectra XT (2)	52	42.5	18.27	41.1	96.71
	103	94.3	8.45	93.0	98.62
	206	179.7	12.77	178.1	99.11
	387	325.1	15.99	323.9	99.63
Ladybug	100	238.2	138.20	9.3	3.90
	500	549.2	9.84	17.3	3.15
	1000	821.3	17.87	28.9	3.52
Delta Light	100	459.2	359.20	47.5	10.34
	500	620.3	24.06	63.3	10.20
	1500	1178	21.47	112.2	9.52
J-200	100	223.2	123.20	8.895	3.99
	220	221.2	0.55	7.446	3.37
	1000	793.4	20.66	23.57	2.97

Source: Unpublished own data. Measurements conducted at Scintilum facilities (www.scintilum.com.br).

Unfortunately, available photoelectric sensors for measuring pigment removal lasers (Q-switched Nd:YAG), such as those from Ophir,[13] Coherent,[14] and Gentec,[15] do not distinguish between wavelengths present in the measured beam. These sensors are crucial for product certification bodies (PCBs) tasked with approving equipment for metrological and health authorities. As a result, technical reports do not accurately reflect the 532nm laser dose delivered to patients according to screen settings but instead aggregate coaxial 532nm and 1064nm beams, leaving the 532nm component undetermined for metrological assessments.

The only exception noted in our tests is the Spectra XT by Lutronic, featuring a distinct photonic system where beam generation, amplification, and control—including second harmonic generation—occur within the equipment's main engine rather than the handpiece. The resultant beam is then guided through an articulated arm with mirrors to the treatment area.

The photonic system of the Spectra XT restricts user mechanical adjustments of optical components as they are pre-set. A higher complexity in second harmonic generation was also observed, with the use of a larger, high-quality pre-heated KTP crystal monitored by equipment software to prevent

532nm emission from a cold crystal and minimize risks of photochromic damage, such as gray tracking.[16] The system also includes dichroic filters for wavelength discrimination, making it the only equipment in the study capable of providing a monochromatic 532nm intensity relatively aligned with screen specifications, complying with the NBR/IEC 60.601-2.22 standard.

Some laser systems, such as Contourline's Inkie, incorporate a phase matching angle adjustment ring for crystal-based energy adjustments. However, user manuals often omit this requirement, and operational training does not consistently cover it.[17] Another difficulty in adjusting the position of the KTP crystal in relation to the phase matching angle is the lack of affordable energy meters to monitor maximum energy levels. As the KTP is removable in these devices, readjustment is necessary with each reinstallation and use.

Notably, the lack of spectral discrimination in coaxial beam components may intentionally obscure technical limitations related to KTP crystal quality, as most lower-cost components have poor second harmonic generation conversion rates. A similar discrepancy in pigment removal lasers is observed regarding deviations between screen-set low energy values and actual measured beam exit values, often exceeding 150% of the administered dose due to solid-state laser cavity instability at low energies. Consequently, laser source parameters are adjusted to ensure reliable operation even at minimum screen energy settings, often resulting in intentional firing at higher energies (e.g., 200mJ minimum for lasers with initial settings of 20 to 100mJ), compromising compliance with the NBR/IEC 60.601-2.22 standard, which mandates maximum deviations of 20% between selected and measured values.

FINAL CONSIDERATIONS

For medical professionals aiming to achieve optimal clinical outcomes in managing epidermal pigmented lesions or performing tattoo removal, selecting tools endorsed by industry expertise and approved by the competent bodies is of paramount importance. However, with the exception of the Lutronic Spectra XT, none of the 1064nm lasers analyzed in this study demonstrated sufficient conversion efficiency to 532nm. This inefficiency compromises the effective removal of residual red and/or orange pigments, as indicated values on screens do not align with actual measurements at the laser output window. Our analyses also highlight potential methodological flaws in laser measurements by PCBs concerning compliance with the NBR/IEC 60.601-2.22 standard for INMETRO and subsequent ANVISA approval of Class 3 laser equipment. Further studies with a larger sample size are needed to determine whether the observed trends are limited to the devices tested or are widespread. Future research should also investigate the risks associated with administering 1064nm and 532nm wavelengths simultaneously on the same treated area, given the misleading screen information suggesting that only 532nm is being administered at an energy level equivalent to 50% of the resultant beam. Additionally, evaluations of user manuals should be conducted to ensure regulatory compliance regarding the use of KTP crystals for generating the 532nm laser beam. ●

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