ISSN 1855-9913

Journal of the Laser and Health Academy
Vol. 2013, No.1; www.laserandhealth.com

Characterization of Laser Tattoo Removal Treatment Using Pulsed Photothermal Radiometry

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ABSTRACT

Pulsed photothermal radiometry (PPTR) enables noninvasive determination of temperature depth profiles induced in strongly scattering biological tissues and organs, including human skin, by pulsed laser irradiation. In the present study, we evaluate the potential of this technique for objective characterization of a laser tattoo removal procedure.

The study involved 5 healthy volunteers (age 20–30 years) undergoing tattoo removal treatment using a Q-switched Nd:YAG laser. Four measurement and treatment sessions were performed over a time period of 10 months. Prior to each treatment, PPTR measurements were performed on several tattoo sites and one nearby healthy site in each patient, using a 5 μs Nd:YAG laser at low radiant exposure values and a dedicated PPTR setup. The laser-induced temperature profiles were reconstructed using a custom numerical optimization code. In addition, each tattoo site was documented with a digital camera and measured with a custom colorimetric system (in tristimulus color space), providing an objective evaluation of the therapeutic efficacy to be correlated with our PPTR results.

The laser-induced temperature rise in previously untreated tattoos was maximal at a subsurface depth of ~300 μm. In tattoo sites that responded well to laser therapy, a significant drop of the temperature peak was observed in the subsequent temperature depth profiles. In several sites which appeared much less responsive according to photography and the colorimetric record, a progressive shift of the laser-induced temperature profile deeper into the dermis was observed over the course of consecutive laser treatments, indicating that the tattoo removal procedure was nevertheless effective.

Keywords: laser tattoo removal, pulsed photothermal radiometry, temperature depth profiling, colorimetry

Article: J. LA&HA, Vol. 2013, No. 1; pp. 68-74.
Received: May 7, 2013; Accepted: July 8, 2013.

Printed in Europe. www.laserandhealth.com

I. INTRODUCTION

The introduction of the concept of selective photothermolysis by Anderson and Parrish in 1983 [1] has made it possible to conceive laser removal of tattoos without damaging the surrounding skin. Nowadays, this approach is the most favorable method of removing unwanted tattoos.

The basic mechanism of laser tattoo removal is the targeting of tattoo particles with selectively absorbed light. As the very short laser pulses are accumulated in tattoo particles, the latter are inhomogenously heated and broken into smaller pieces by build-up of mechanical stress. Meanwhile, the overlying epidermis is protected from nonselective thermal injury by active cooling.[2] Following the treatment, macrophages engulf the particle debris by endocytosis and the tattoo is gradually removed.[3-5]

Nevertheless, laser treatment of tattoos can occasionally result in adverse side effects and complications such as transient or permanent hypopigmentation, hyperpigmentation, scarring, infection, bleeding – or simply ineffective partial removal or even darkening of tattoo ink.[3-5] Therefore, new laser systems and treatment protocols are being continuously developed to increase the efficacy and reduce complications of laser tattoo removal. In addition, subjective visual assessment of therapy progress is inaccurate, which makes the planning of individual laser therapies difficult.

A practical means for objective, quantitative evaluation of the therapeutic efficacy of laser tattoo removal is therefore needed. In this study, we monitored tattoo removal treatment using photography, colorimetry, and pulsed photothermal depth profiling (PPTR). The first two techniques are used to determine only the visual appearance of the tattoo after treatment. In contrast, PPTR provides a temperature depth profile of the tattoo after laser irradiation, and thus enables greater insight into the tattoo removal process.

II. PATIENTS AND METHODS

This study involved 5 healthy volunteers (3 males, 2 females), of age 20–30 years, undergoing tattoo removal treatment. The patients were of Fitzpatrick skin type I–III. Table 1 shows the locations and colors of the studied tattoos for each involved volunteer.

Table 1. Locations and colors of tattoos in the 5 volunteers involved in the study

Patient	Location	Color
#1	calf	black
#2	hand	blue, red
#3	forearm	black
#4	neck, hand	black
#5	abdomen	cyan, red

A Q-switched Nd:YAG laser with 6 ns pulses (QX MAX, Fotona, Ljubljana, Slovenia) was used for therapy. At the first visit, the radiant exposure ranged between 5.5 and 8.0 J/cm². After 6 weeks the treated tattoo was assessed and subsequent dosage was adjusted according to the observed outcome. Patients were seen at 2 to 3-month intervals.

Prior to each treatment, digital photographs, colorimetric measurements, and radiometric measurements were obtained. There were four measurement and treatment sessions in total, spread over a time period of 10 months (in March, May, October, and January, respectively). As is customary in laser therapy, treatments were not performed during the summer months, because of increased risk of nonselective injury due to sun tan.

Colorimetry is often used to quantitatively assess therapeutic efficacy in laser procedures.[6,7] In this study we used a colorimeter (PocketSpec Color QA Version 5.0, PocketSpec Technologies Inc., CO), which measures tristimulus color coordinates *X, Y,* and *Z* (CIE 1931)[8] emulating the process of human color vision. These color coordinates are transformed into perceptually uniform color space (CIE 1976)[9] to provide an estimate for human perception of color. Here, color coordinates L^*, a^*, and b^* represent skin brightness, yellowness, and redness, respectively.

Colorimetric measurements were performed on two tattoo sites and one nearby healthy site in each patient using our custom software for evaluation of dermatologic laser treatments. For objective assessment of laser therapy effectiveness, we monitored the color difference, $\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}$, which is the Euclidian distance in the perceptually uniform color space between the measurements on the tattoo site and normal skin. Note that the color difference of $\Delta E = 1$ corresponds to the same (barely perceptible) color contrast at any point in the CIE 1976 color space.

PPTR is based on measurement of the transient change of IR emission from a laser-heated tissue following pulsed laser irradiation. The radiometric signals can then be used to reconstruct the depth-resolved temperature distribution immediately after the irradiation. The theoretical background and system description were described previously.[10,11]

PPTR measurements were performed on two tattoo sites and one nearby healthy site in each patient. Each PPTR measurement involved irradiation of the site with a single 5 μs pulse from a Nd:YAG laser at 1064 nm. The radiant exposure was ~7 J/cm², which is significantly lower as compared to the subsequently applied therapeutical values. Infrared radiation emitted from the center of the irradiated area was collected by a pair of plano-convex Si lenses (Galvoptics, Essex, UK) positioned for total magnification of $M = 1$. The lenses were coated for high transmittance in the acquisition spectral band of the single-element InSb detector (P5968–100, Hamamatsu; λ = 3.0–5.6 μm) with a diameter of 1 mm and 45° field of view.

For each measurement, a 2 ms long radiometric signal was recorded at the acquisition rate of 50,000 Hz. The corresponding PPTR transient was obtained by a calibration procedure and subtraction of the baseline level. This was used as input to our custom multidimensional optimization algorithm to reconstruct the initial laser-induced temperature profile. Details of the reconstruction process can be found elsewhere.[12,13]

At each measurement session, we have also documented the visual appearance of the tattoos by digital photography.

III. RESULTS

a) Good responder

Figure 1 presents photographs of the tattoo of patient #1 taken before laser therapy (Fig. 1a) and after three consecutive therapies (Figs. 1b–d). The site where colorimetric data and PPTR signals were measured is marked by a black arrow. Evidently, tattoo bleaching was significant after each laser therapy, and after the third laser therapy the tattoo was almost cleared (Fig. 1d).

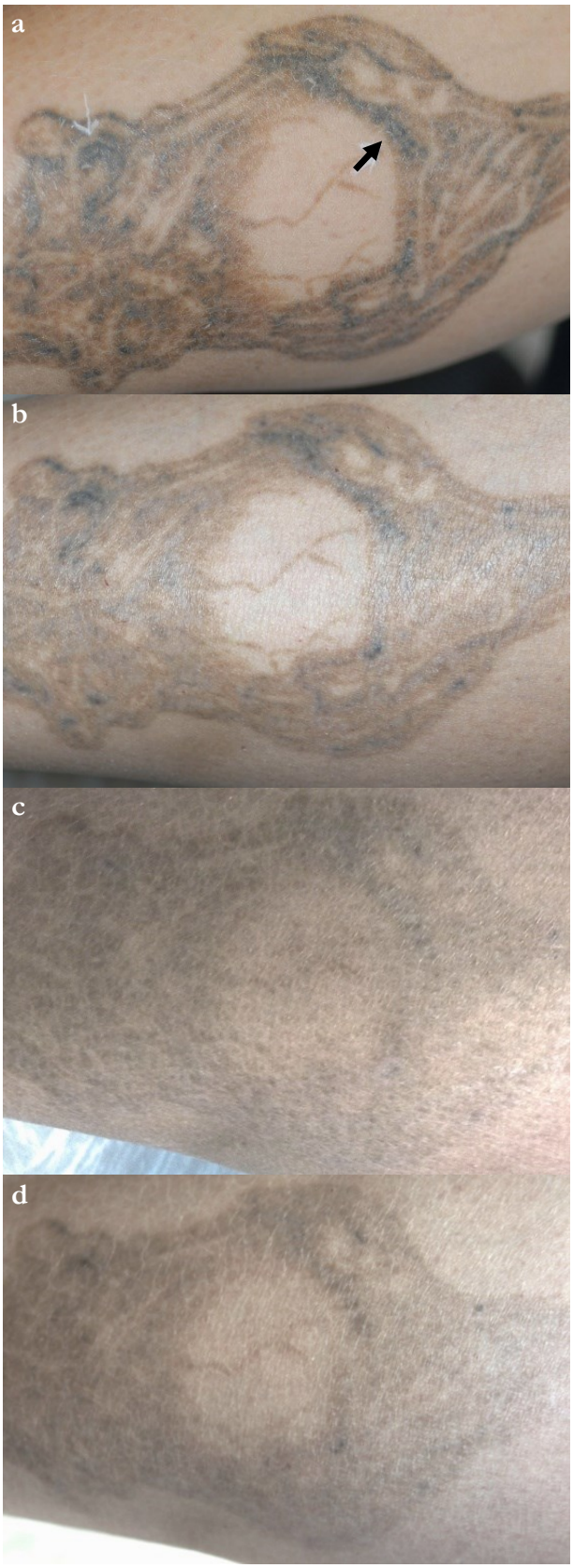

Fig. 1: Photographs of the tattoo in patient #1 taken at visits #1–4 (photographs a–d, respectively). The measurement site is marked by the arrow.

Colorimetric data measured on patient #1 in terms of three components of the color vector (L^*, a^*, b^*) are displayed in Figure 2. The tattoo is darker, somewhat redder, and less yellowish than nearby normal skin. The most prominent change over the course of laser therapy is a progressive decreasing of the difference between the brightness (L^*) of normal skin and the tattoo (*Fig. 2, top panel*).

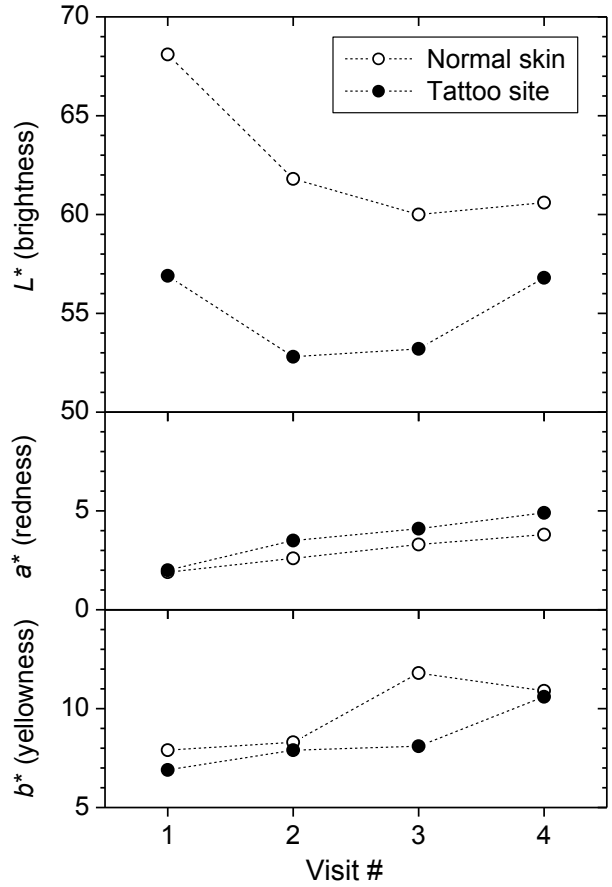

Fig. 2: Brightness (L^*), redness (a^*), and yellowness (b^*) of the tattoo site (*solid circles*) and nearby normal skin (*open*) as measured on patient #1 during the four visits.

The brightness (L^*) of normal skin shows significant seasonal variation (*top panel*). Thus, the corresponding L^* value decreases from visit #1 in March till visit #3 in October, and then raises slightly toward the last visit in January. This is a result of increased melanin concentration in the epidermis. For the tattoo, the same trend is superimposed onto bleaching of the tattoo, evidenced by the difference between the L^* values for normal skin and the tattoo, which reduces to approximately one third of the initial value over the course of therapy.

The redness (a^*) of tattoo is only marginally larger than that of normal skin and the difference is Similarly, all yellowness values (b^*) are very similar, except during visit #3. Since this visit took place in the fall (October), the larger value of b^* in normal skin could be due to an increased concentration of melanin

as a result of sun tanning, while the tattoo site was not affected to the same degree.

Figure 3 presents projections of the color difference vectors $\Delta \boldsymbol{E}$ onto the planes (L^*, a^*) and (L^*, b^*). The start of each arrow indicates colorimetric values as measured in normal skin, and the end indicates the values for the tattoo. The projections clearly illustrate the trend of the color difference vector changing with laser therapies. With each successive therapy, the brightness component of the color difference vector is monotonically decreasing. At the same time, redness is gradually, but monotonically increasing (Fig. 3a). In the (L^*, b^*) plane the general trend of increasingly more yellow skin with each successive therapy is interrupted on visit #3, which is due to significantly increased skin tone as a result of sun tanning in normal skin.

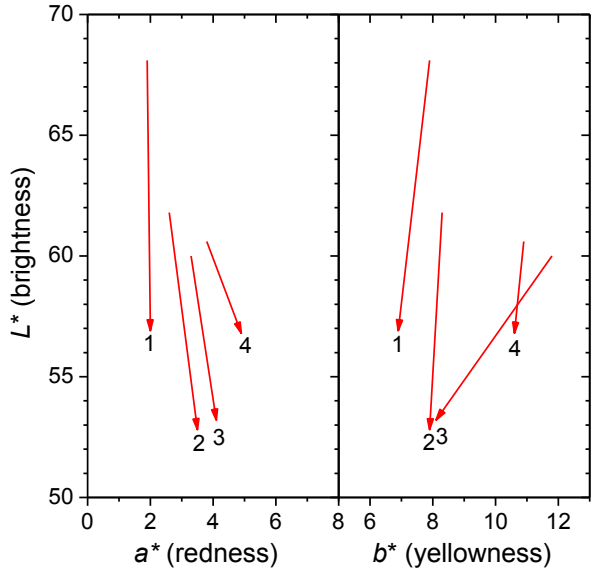

Fig. 3: Color difference vectors between the normal skin (*arrow start*) and tattoo (*arrow end*) for patient #1 as measured during the four visits (*see the labels*) projected onto planes (ΔL^*, Δa^*)(*left panel*) and (ΔL^*, Δb^*)(*right*).

The analysis of colorimetric data is rather indirect and inconclusive, since each measurement consists of three color coordinates for normal and non-normal skin (Figs. 2 and 3), respectively, and each of the measured coordinates is prone to certain measurement error. Also, seasonal variations of skin color are present since measurements were performed at different times of the year.

PPTR signals measured on patient #1 are presented in Figure 4. Both signals increase abruptly after pulsed laser irradiation. In normal skin (*red line*) the signal then decreases monotonically, indicating that the majority of absorbers are located close to the skin surface (melanin). In the tattoo (*black line*), the signal initially increases until ~0.5 s, and then slowly starts to decrease, indicating the presence of a relatively thick, strongly absorbing structure deeper inside the skin.

Figure 5 presents the reconstructed temperature profiles for patient #1 at different visits. At the tattoo (Fig. 5a), a major temperature rise in the dermis is observed during visit #2 (*black line*), with the peak value of 11.8 K at a depth of 0.35 mm.

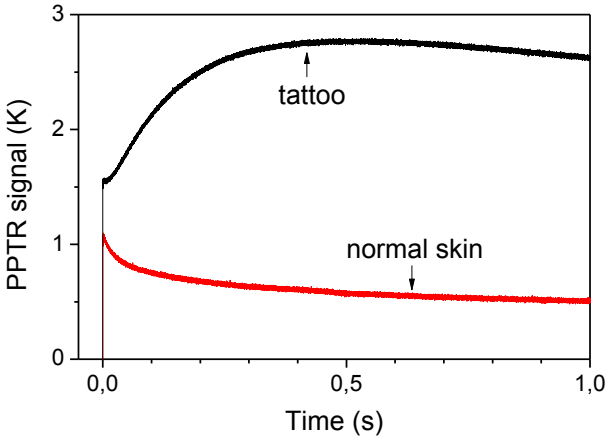

Fig. 4: PPTR signals measured on the tattoo (*black line*) and nearby normal skin (*red*) in patient #1 during visit #2.

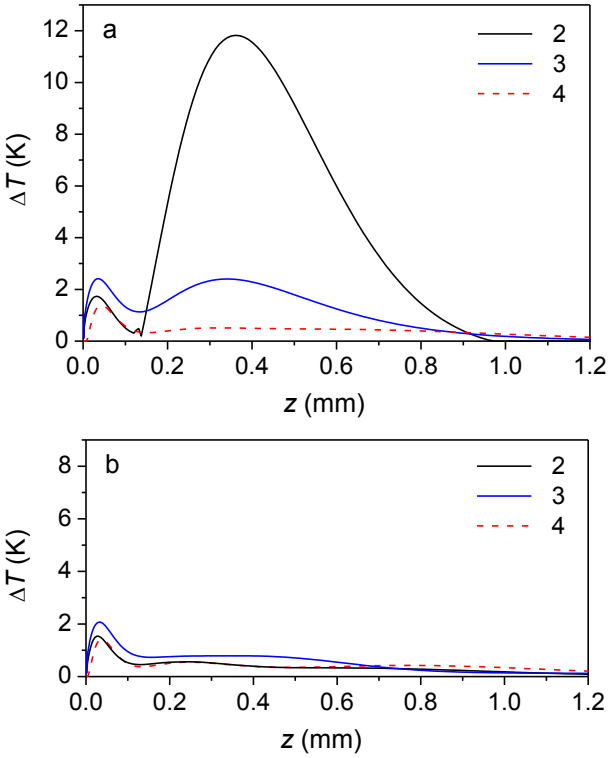

Fig. 5: Reconstructed temperature profiles in the tattoo site B of patient #1 (a) and nearby healthy skin (b). Measurements were performed prior to laser treatment on visits #2 (*black solid line*), 3 (*blue*), and 4 (*red, dashed*).

The temperature rise at that depth decreases markedly with each successive treatment, with the

amplitude dropping to 0.5 K by visit #4 (*red, dashed line)*. This clearly shows that laser treatment successfully reduces the concentration of tattoo pigment in the upper dermis. The temperature rise in the most superficial 0.10 mm thick layer, which can be seen also in normal skin (Fig. 5b), corresponds to laser light absorption in the epidermal melanin. The rather uniform temperature rise at larger depths corresponds to hemoglobin absorption in dermal blood vessels.

In Figure 6 the color differences ΔE are compared with maximum temperature amplitudes ΔT from reconstructed temperature profiles for patient #1. Temperature amplitudes show a progressive decrease with each therapy indicating a successful clearing of the absorbing pigment. The total decrease of ΔT is 96%. Similarly, a gradual decrease of ΔE is observed. The total reduction of ΔE is 65%.

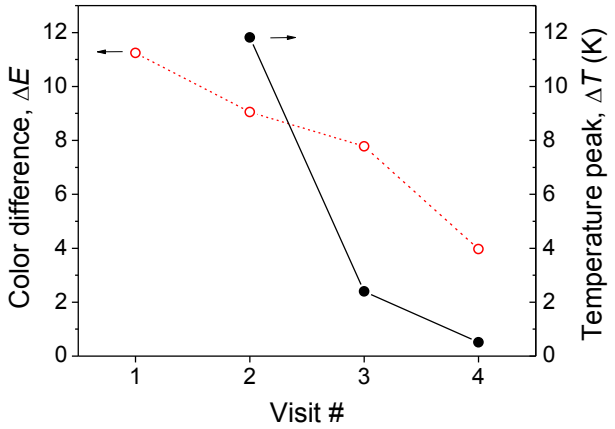

Fig. 6: Color difference ΔE (*open symbols*) and maximal temperature rise ΔT (*solid symbols*) as measured in patient #1 over the course of laser therapy.

In the presented example, all three techniques agree that the patent #1 has responded well to laser therapy. The concentration of tattoo pigment in the upper dermis was evidently markedly reduced with each successive treatment.

b) Poor responder

Photographs of the tattoo in patient #2 are presented in Figure 7. The presented sequence does not show any noticeable clearing of the tattoo after three laser therapy sessions.

The relative reduction of ΔE (Fig. 8) over the course of the entire laser therapy is rather small (4%), especially when compared to that observed in patient #1 (see Fig. 6). In contrast, the corresponding relative reduction of ΔT as determined from PPTR measurements is significant (32%).

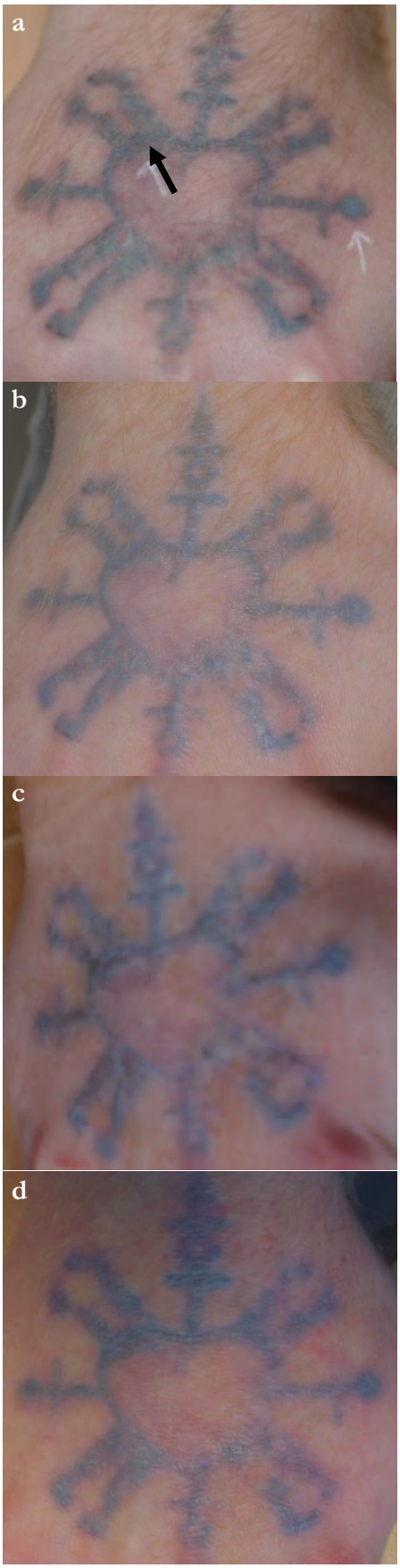

Fig. 7: Tattoo images of patient #2 taken during visits #1–4 (photographs a–d, respectively). The measurement site is marked by the arrow.

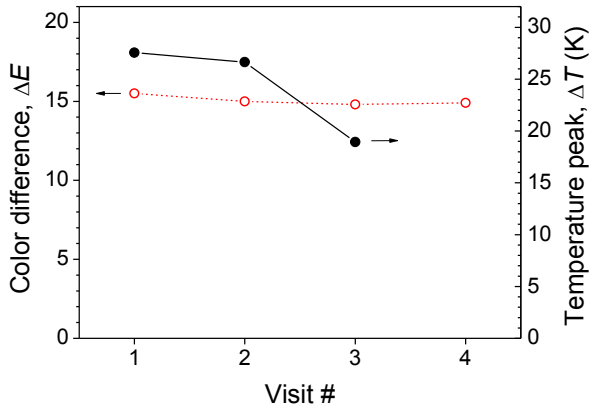

Fig. 8: Color difference ΔE (*open symbols*) and amplitude of PPTR temperature profile ΔT (*solid symbols*) for patient #2 (PPTR measurements during the visit #4 were not successful).

However, a closer analysis of the corresponding temperature depth profiles (Fig. 9) reveals a gradual shifting of the laser-induced temperature rise to larger depths with peak values getting somewhat lower with each consecutive treatment session. Our PPTR analysis thus demonstrates that laser treatments are gradually eliminating the tattoo on a layer-by-layer basis. We can thus conclude that laser treatment at current settings is effective and the tattoo would likely be completely removed by a few additional treatments.

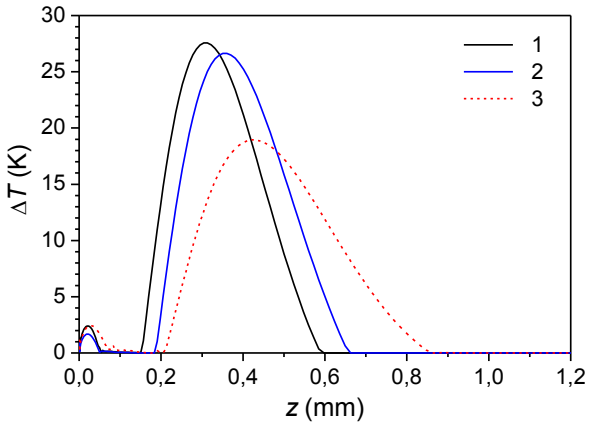

Fig. 9: Temperature depth profiles in the tattoo site on patient #2 as reconstructed from PPTR measurements on visits #1–3 (*see the legend*).

Meanwhile, the negative assessment of treatment efficacy by both visual observation (Fig. 7) and colorimetry (Fig. 8), most likely results from the larger thickness and/or concentration of the tattoo pigment layer. Thus, even despite the partial degradation of the tattoo, there was still enough pigment left in the skin to dominate the visual impression and colorimetric measurements.

IV. DISCUSSION

Inspection of photographs is a common technique for monitoring the success of cutaneous laser treatments. However, this is clearly a rather qualitative approach, based on subjective visual impression and prone to artifacts due to ambient lighting, camera settings, etc.

Colorimetry provides an objective approach to treatment monitoring, which also lends to more accurate quantitative analysis. Perhaps the most prominent limitation of this approach results from significant seasonal variations of skin coloration (see Figs. 2, 3). Consequently, one must always consider the difference between the lesion site and nearby normal skin, which emphasizes the measurement error.

Moreover, colorimetic measurements usually involve relatively large areas (6 mm in diameter in our example), which makes analysis of any small lesions quite inaccurate. In addition, the amount of instrument pressure onto the skin may influence hemodynamics and thus affect color readings. As a result, colorimetric data are reliable only when the color difference ΔE is sufficiently large.

In contrast to the above, our PPTR technique provides information on local depth distribution of subsurface absorbers, and is not prone to most of above mentioned artifacts.

As demonstrated in the presented example of patient #3, even when the former techniques assess laser treatment as ineffective, PPTR profiling can pick up the partial removal of tattoo pigment, therefore providing unparalleled insight into the laser treatment process.

One should note, however, that PPTR profiling belongs to a group of severely ill-posed inverse problems. As a result, extreme attention to details, from the experimental setup and parameters, to selection and implementation of numerical optimization algorithms, must be exercised in order to obtain accurate and robust reconstructions.[12]

A summary of the obtained patient results is presented in Table 2 (one tattoo site per patient only). The treatment efficacy as assessed by gross inspection of digital photographs (Yes/No), relative change of color difference (ΔE), and relative change of the peak temperature value (ΔT) is presented for the 5 volunteers and first three treatment visits.

Table 2. Efficacy of laser therapy as determined subjectively from photographs (Y – yes, N – no), relative change in color difference (ΔE), and relative change in maximal temperature rise (ΔT) after the first three treatment sessions (Tx).

Patient	Tx	Visual	ΔE	ΔT (K)
#1	1	Y	–20 %	
	2	Y	–14 %	–80 %
	3	Y	–49 %	–79 %
#2	1	N	–3 %	–3 %
	2	N	–1 %	–29 %
	3	N	+1 %	
#3	1	N	–12 %	
	2	N	+10 %	+30 %
#4	1	Y	–41 %	
	2	Y	–52 %	–54 %
	3	Y	–14 %	–13 %
#5	1	N	–7 %	
	2	N	–27 %	–61 %
	3	N	–47 %	–18 %

A very good response to laser therapy is observed in patients #1 and #4, as is evident from all three approaches (compare with Figs. 5, 6).

For patient #3, in contrast, none of the three techniques indicates any significant progress toward removal of the tattoo.

For patients #2 and #5, the visual appearance of the tattoos didn't change much after the treatment sessions, which is reflected also in colorimetric measurements. Yet, the reconstructed temperature profiles revealed that tattoo pigment was being gradually degraded and removed (Figs. 8, 9).

V. CONCLUSIONS

PPTR temperature profiling enables quantitative assessment of laser tattoo removal. In contrast with photography and colorimetry where only visual appearance is assessed, PPTR provides objective information on depth distribution of tattoo pigment, thus providing an unparalleled insight into the tattoo removal process. Access to such information might allow guidance and optimization of therapy on an individual-patient basis.

Acknowledgements

The authors acknowledge Fotona d.d. for the loan of laser equipment and volunteer logistics, and Irena Bacak for performing the laser treatments.

This research was carried out in a collaboration with the EU regional Competency Center for Biomedical Engineering (www.bmecenter.com), coordinated by Laser and Health Academy (www.laserandhealthacademy.com), and partially supported by the European Regional Development Fund and Slovenian government.

REFERENCES

1. Anderson RR., Parrish JA. Selective photothermolysis: precise microsurgery by selective absorption of pulse radiation. Science 1983; 220:524–527.
2. Nelson JS, Milner TE, Anvari B, Tanenbaum BS, Kimel S, Svaasand LO, Jacques SL. Dynamic epidermal cooling during pulsed-laser treatment of port-wine-stain — A new methodology with preliminary clinical evaluation. Arch Derm 1995; 131:695–700.
3. Kuperman-Beade M, Levine VJ, Ashinoff R. Laser removal of tattoos. Am J Clin Dermatol 2001; 2(1): 21–5.
4. Bernstein EF. Laser tattoo removal. Semin Plast Surg 2007; 21(3): 175–92.
5. Elsaie ML, Nouri K, Vejjabhinanta V, Rivas MP, Villafradez-Diaz LM, Martins A, Rosso R. Topical imiquimod in conjunction with Nd:YAG laser for tattoo removal. Lasers Med Sci 2009; 24(6):871–5.
6. Wagner BT, Kline D. Introduction to the bases of colour vision. 2002; http://www.psych.ucalgary.ca/PACE/VA-Lab/Brian/default.htm
7. Majaron B, Milanič M, Knez M. Colorimetric analysis of seasonal, daily, and acute variations of skin color. Laser Surg Med 2010; 42 (22):10–11.
8. Smith T, Guild J. The C.I.E. colorimetric standards and their use. Trans Opt Soc 1931; 33(3): 73–134.
9. McLaren K. XIII—The Development of the CIE 1976 (L* a* b*) uniform colour space and colour-difference formula. J Soc Dyers Colourists 1976; 92(9):338–41.
10. Milner TE, Goodman DM, Tanenbaum BS, Nelson JS. Depth profiling of laser-heated chromophores in biological tissues by pulsed photothermal radiometry. J Opt Soc Am A 1995; 12:1479–88.
11. Majaron B, Milanič M. Effective infrared absorption coefficient for photothermal radiometric measurements in biological tissues. Phys Med Biol 2008; 53:255–68.
12. Milanič M, Serša I, Majaron B. Spectrally composite reconstruction approach for improved resolution of pulsed photothermal temperature profiling in water-based samples. Phys Med Biol 2009; 54:2829–44.
13. Milanič M, Majaron B. Comparison of binning approaches for pulsed photothermal temperature profiling. Proc SPIE 2008; vol. 7371, 737100-1–8.