Subsurface temperature monitoring during hyperthermic laser treatment

Košir J[(1,2)*], Vella D[(2)], Lukač M[(1,3)], Jezeršek M[(2)]

(1) Fotona d.o.o., Ljubljana, Slovenia
(2) Faculty of Mechanical Engineering, University of Ljubljana, Ljubljana, Slovenia
(3) Department of Complex Matter, Jozef Stefan Institute, Ljubljana, Slovenia

*Corresponding author's email: jure.kosir@fotona.com

Background – Advancements in medical laser technology have paved the way for its widespread acceptance in a variety of procedures. Selectively targeting tissue structures with minimally invasive procedures limits the damage to surrounding tissue and shortens post-procedural downtime. Effectiveness of such therapies strongly relies on the ability to closely monitor the temperature of the targeted tissues. These are usually located in the subsurface regions, thus high-energy visible and infrared lasers in combination with surface cooling systems are employed [1–3]. Temperature peak is thus located well below the tissue surface and can be significantly higher than skin temperature (10– 20 °C) [1, 2]. Current approaches for monitoring subdermal temperature are either invasive, complex or offer inadequate spatial resolution [4]. Furthermore, numerical studies are often therapy–tailored and source tissue parameters from the literature, lacking versatility and a tissue–specific approach. In our previous study a time–dependent algorithm was conceptually showcased [1]. We further modified the algorithm for heterogeneous tissues and performed ex–vivo validation study [2]. Here, we present its extended applicability to in–vivo tissues and its implementation with hand–held laser scanner head. Additionally, algorithm recognizes tissue–specific thermal characteristics yielded by a fast calibration process. The algorithm was showcased in–vivo during a Hyperthermic Laser Treatment (HTLT).

Methods – The estimation of thermal parameters (ETP) setup included a 2,940 nm Er:YAG laser source (Dynamis SP, Fotona, Slovenia). The laser beam illuminated the surface through a diverging lens, effectively producing a laser spot approx. 6 cm in diameter. The heating cycle was performed for 30 s with an average intensity I=0.1 W/cm^2 and VLP mode ("Very Long Pulse", pulse duration t_p=1,000 µs, repetition rate f_r=12 Hz). Tissue thermal parameters (thermal diffusivity D, thermal conductivity k and blood perfusion ω) of an individual (28-year-old male with BMI of 32) were yielded by fitting numerically simulated $T_s(t)$ with a measurement recorded during the calibration protocol. After ETP, HTLT was performed in–vivo on 28-year-old individual. Laser system included a hand–held scanner head, which homogeneously irradiated surface area of 5.4 x 5.7 cm^2 for 80 seconds (with Nd:YAG source, 1,064 nm, AvalancheLase LXP, Fotona, Slovenia). In addition, tissue surface was cooled with integrated cooling system. We performed multiple HTLT cycles, each with prolonged active cycle duration (form t_1=40 to t_4=120 s). Cooling settings and average intensity of irradiation I=1.2 W/cm^2 remained constant. During each measurement the temporal evolution of $T_s(t)$ was recorded with newly introduced supervision module that features multiple thermal sensors and RGB camera. The module was integrated within a hand–held scanner head. The $T_s(t)$, recorded during HTLT, were used in STD algorithm to estimate $T(z)$ for each performed HTLT cycle.

Results: During ETP a calibration measurement was performed. The surface temperature response to laser irradiation and the following thermal relaxation reflected the behaviour already reported in other studies. Recorded T_s was well reproduced by numerical model [2] as depicted in Fig. 1, left panel. Estimated thermal parameters were D_s=1.05·10^{-7}, D_f=1.23·10^{-7} m^2/s, k_s=0.42 and k_f=0.31 W/m^{2}K.

Additionally, blood perfusion rates were estimated as ω_s=0.84 and ω_f=0.28 kgm^3/s for skin and fat respectively. Obtained tissue parameters were used in STD algorithm [2] for estimations of $T(z)$ during in–vivo performed HTLT. Estimated $T(z)$ are depicted in right panel of Fig. 1 for each active cycle duration.

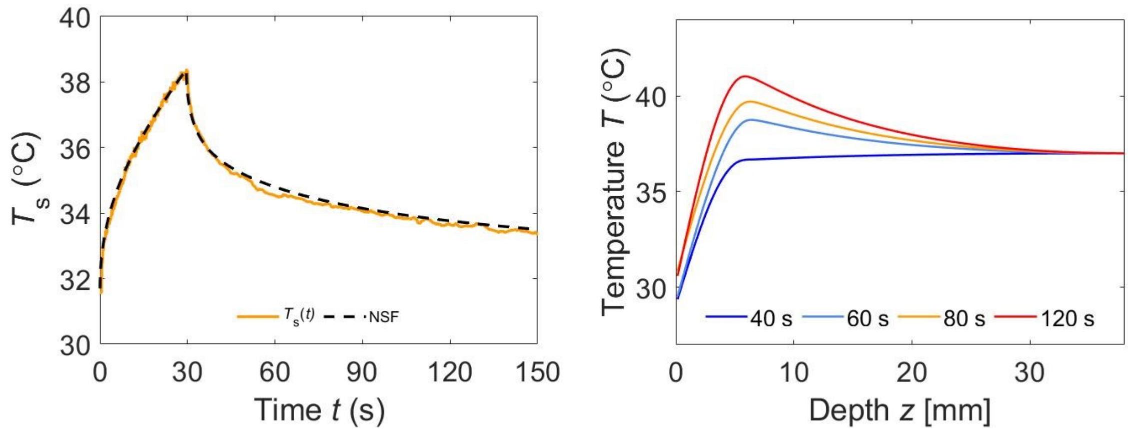

Fig. 1. In–vivo performed HTLT. Left panel depicts recording of $T_s(t)$ during ETP protocol (in yellow) along with numerical simulation fit (NSF). Right panel depicts $T(z)$ estimated during HTLT as irradiation time was prolonged from 40 to 120 s.

The peak's locations z_{max} were estimated to range 5–6 mm from the irradiated surface. This particular range is consistent to the one obtained in the skin–fat sample [2]. The peak temperature T_{max} was trending higher with prolonged irradiation times as depicted in Fig. 1, right panel. In addition, results of in–vivo study presented by Milanič et al. [3] correlate well with our $T(z)$ estimations in regard to temperature distributions, temperature peak values and locations. At t_3=80 s we performed a set of measurements to asses repeatability of treatment's outcome. Within the set of estimated $T(z)$ an average error was ±0,4 mm and ±0,6 °C for z_{max} and T_{max} respectively.

Conclusion: We presented an in–vivo application of a novel approach for estimation of the tissue's thermal parameters ETP and subsurface temperature distribution within tissue after laser irradiation. The estimated $T(z)$ during in–vivo HTLT showed a trend that is comparable to reports of other in– vivo studies. Furthermore, peak temperatures and positions were within range of reported values. The presented method for subsurface temperature monitoring was implemented in a newly developed supervision module that is integrated within a hand–held laser scanner head.

References

[1] M.A. Lewis, R.M. Staruch, R. Chopra, Thermometry and ablation monitoring with ultrasound, Int J Hyperthermia 31:2 (2015) 163–181. doi:10.3109/02656736.2015.1009180.

[2] J. Košir, D. Vella, M. Jezeršek, Non-contact monitoring of the depth temperature profile for medical laser scanning technologies, Sci. Rep. 10, 20242 (2020). https://doi.org/10.1038/s41598-020-77283-9.

[3] J. Košir, D. Vella, M. Lukač, M. Jezeršek, Towards personalized and versatile monitoring of temperature fields within heterogeneous tissues during laser therapies, Biomed. Opt. Express 12:7 (2021) 4530–4543. https://doi.org/10.1364/BOE.428028.

[4] M. Milanič, B.T. Muc, N. Lukač, M. Lukač, Numerical study of hyper–thermic laser lipolysis with 1,064 nm Nd:YAG laser in human subjects, Lasers Surg. Med. 51:10 (2019) 897–909. https://doi.org/10.1002/lsm.23124.