Infinite Science
Publishing

# Towards data-driven predictive temperature control for retinal laser treatments

**A.-K. Poetschki[1*], M. S. Huch[1], H. Volkens[1], H. S. Abbas[2], and R. Brinkmann[1,3]**

[1] *Medical Laser Center Lübeck, Lübeck, Germany*

[2] *Institute for Electrical Engineering in Medicine, University of Lübeck, Lübeck, Germany*

[3] *Institute of Biomedical Optics, University of Lübeck, Lübeck, Germany*

[*] *Corresponding author, email: andra-karina.poetschki@uni-luebeck.de*

*Laser-induced coagulation is a common treatment of retinal diseases. Manual dosing is prone to error and can lead to extended damage of the neural retina. We elaborated a novel data-driven predictive temperature control (DPC). To identify controller hyperparameters with minimal deviation from the target temperature extensive simulation was carried out, based on 206 measured data sets, each applied pulse energy and induced temperature rise. This resulted in a median and mean deviation from the target temperature of 1.6 °C and 2.6 °C (95 % CI = 2.3 - 3.1 °C), respectively. In addition, we developed a detection algorithm for eye movements (saccades), optimized with Bayesian Optimization that achieved detection sensitivity of 92 % and specificity of 100 %. The experience with Bayesian Optimization shall be used to further optimize the DPC and to evaluate clinical data.*

## I. Introduction

Laser irradiation is a common treatment of retinal diseases, such as diabetic retinopathy, macular edema or retinal detachment. The therapeutic effect ranges from thermal stimulation to photocoagulation, whereby dosing is often done manually by the ophthalmologist. This is prone to error, because fundus absorption varies strongly. When using the same laser power, this results in irradiations ranging from strong damage to the neural retina to inefficient undertreatment.
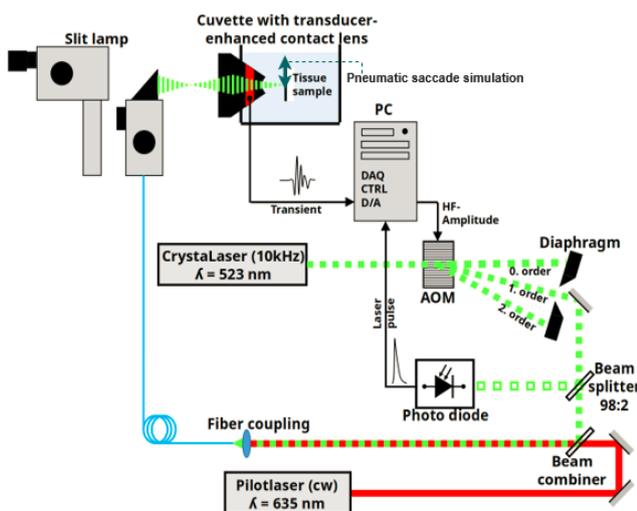


*Figure 1: Schematic representation of the experimental set-up (edited from [1]). For irradiation (10 kHz) and optoacoustic temperature measurement (1 kHz) the same CrystaLaser (Nd:YLF, τ ≈ 160 ns) is used. Based on induced pressure transients, and the calculated temperature, the implemented controller computes the signal for the acousto-optic modulator (AOM) that determines the amount of energy that is diffracted into the first order which is then used for the next irradiation pulse.*

A clinical study with PID controlled laser irradiation[2] showed that movements of the eye, saccades, pose an additional problem. However, by optoacoustics a real-time temperature determination with high frequency in kHz range is feasible. By modulating the laser power depending on the closed-loop temperature feedback, a target temperature can be addressed. The feedback for the controller, which is the optoacoustically determined temperature at the irradiated spot (see section II), strongly depends on the calibration at the beginning of the irradiation. The calibration contains information about local absorption and scattering, among others. When the spot changes, the calibration and thus the temperature feedback often becomes inaccurate. Therefore we elaborated a novel data-driven predictive control (DPC) approach that eliminates the need for modelling the system[3], and completely relies on input and output data.

## II. Material and Methods

The experimental set-up for measurements and data acquisition is shown in Fig. 1. Heating and **optoacoustic temperature measurement** are done by the same pulsed laser, at different frequencies, 10 and 1 kHz respectively. A piezoelectric ring transducer embedded in the contact lens measures the laser-induced bipolar pressure waves that follow thermoelastic expansion of the absorbers (melanin containing retinal pigment epithelium of ex-vivo porcine eyes). This way the current temperature can be calculated[1,4]. Saccades are simulated by a pneumatic set-up moving the sample (470 μm in 100 ms).

For elaboration of the proposed **DPC** strategy, more than 200 irradiations, with the set-up shown in Fig. 1 and a pre-implemented PID controller, were carried out. These
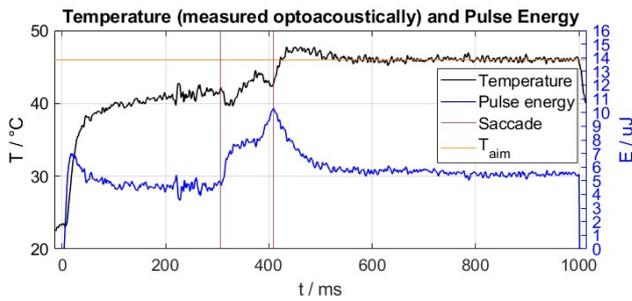
*Figure 2: Exemplary measurement data set, i. e. PID controlled irradiation, pulse energy (blue) and temperature curve (black), with pneumatically simulated saccade (dark red).*

measurement data sets contain information about pulse power and resulting temperature rise, i. e. system input and output data (see Fig. 2). For extensive simulation and tuning of the DPC, 206 of these acquired data sets were used. Targeting a minimal deviation from the aim temperature, DPC with 182 different combinations of hyperparameters (weights of the cost function, Q and R) were applied to each of these measurement data sets, and the temperature resulting from the proposed pulse power was simulated. The temperature increase was modelled using system identification, with coefficients separately identified for each measurement. The DPC was implementted in MATLAB. Its Hankel-predictor is constructed from real-time measurements and its optimization problem, which is the minimization of the cost function, is solved as a quadratic programming (see [3] for details). Fig. 3 shows an exemplary excerpt from the simulation.

## III. Results and Discussion

The extensive **DPC** simulation enabled identification of the best tested combination of hyperparameters. It achieved a median and mean deviation from the target temperature of 1.6 and 2.6 °C (95 % CI = 2.3 - 3.1 °C) respectively, with a mean standard deviation of 2.9 °C and a standard error of 0.2 °C. The results for the absolute deviation from the target temperature are exponentially distributed, i. e. accumulate towards small values. The simulation time for DPC was 60 ms. In 99.5 % of the 37492 simulations at all, the solver provided a feasible solution to the optimization problem.

Currently the DPC is not capable of handling saccades, but an increasing deviation of the predicted temperature from the measured temperature could indicate movement of the eye. An alternative approach is the implementation of a saccade detection algorithm that runs parallel to DPC, which was already developed by our group. It achieved a detection sensitivity of 92 % and a specificity of 100 % (applied to 70 data sets), and was optimized by hint of Bayesian Optimization, that uses probabilistic models to efficiently explore the search space to find the best parameters.

The most challenging problem is measurement noise, especially when it comes to clinical adaption. Noise creates the impression that the data contains much information, without this necessarily being the case. The quantization of the realizable laser powers and the strongly measurement dependent optimal hyperparameters require further considerations.
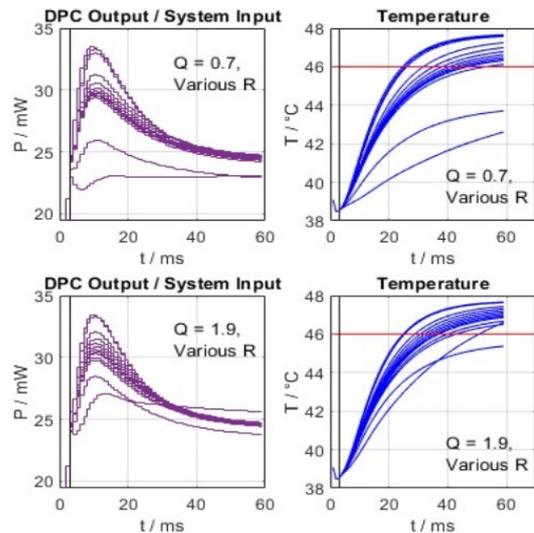


*Figure 3: Excerpt from the DPC hyperparameter tuning. 182 combinations of hyperparameters Q and R were tested on 206 measurement data sets to evaluate deviation from target temperature (red). Shown: Proposed pulse power (DPC output, violet) and simulated temperature rise (blue) for two different values of Q combined with various values of R, applied to one data set.*

Future work for DPC includes better noise handling e. g. by different regularization methods, and exploiting the sparsity of the Hankel matrices used for prediction. Another logical next step is the elimination of the deviation from the target temperature (steady state error) by including an integrator in the control scheme, and utilizing the experience with Bayesian Optimization for target-oriented tuning of the DPC hyperparameters.

## IV. Conclusion

Data-driven predictive temperature control is a promising approach towards safe, uniform and reliable retinal laser treatment. Because of its dynamic online adaptability DPC is more advanced than conservative controllers like PID and possibly able to handle saccades. Alternatively, a combination of DPC and a saccade detection algorithm that is already implemented by our group should be considered. With the detection algorithm we gathered experience with Bayesian Optimization, which will be used in the future to further improve DPC. For applicability DPC and saccade detection need to be evaluated with existing clinical data.

**REFERENCES**
[1] M. Mordmüller et al. *Towards temperature controlled retinal laser treatment with a single laser at 10 kHz repetition rate*, in Advanced Optical Technologies 10.6, 2021, pp. 423–431.
[2] R. Brinkmann et al. *Automatically controlled, non-damaging thermal laser therapy for central serous chorioretinopathy (CSCR)*, in Investigative Ophthalmology & Visual Science 65.7, 2024, pp. 4407–4407.
[3] P. C. N. Verheijen et al. *Handbook of linear data-driven predictive control: Theory, implementation and design*, in Annual Reviews in Control 56, 2023, p. 100914.
[4] R. Brinkmann et al. *Real-time temperature determination during retinal photocoagulation on patients*, in Journal of biomedical optics 17(6), 2012, pp. 061219-061219.