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Assessment of the microcirculation using combined model based diffuse reflectance spectroscopy and laser Doppler flowmetry

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Abstract — By using a combined inverse model for diffuse reflectance spectroscopy (DRS) and laser Doppler flowmetry (LDF) the tissue fraction of red blood cells (RBCs), their oxygenation and speed-resolved perfusion are estimated in absolute units. DRS spectra (450 to 850 nm) are measured at two source-detector distances; 0.4 and 1.2 mm. LDF spectra are measured at 1.2 mm, integrated in the same fiber-optic probe. Inverse Monte Carlo technique and an adaptive tissue model is used to quantify the microcirculatory parameters. Measurements were done during venous occlusion of the tissue. The model fitting yields a good spectral fit for the two DRS spectra and the LDF spectrum. The physiological responses regarding for example which speed regions respond to provocations follows a priori expectations. The combined model gives quantitative measures of RBC tissue fraction, oxygenation and speed resolved perfusion from the same sampling volume which gives new opportunities to interpret data.

Keywords— **diffuse reflectance spectroscopy, laser Doppler flowmetry, modeling, Monte Carlo simulations.**

I. Introduction

The microcirculation is responsible for delivering oxygen to the local tissue through the red blood cells (RBC). Different tissues have different needs and both oxygenation and blood flow are important to consider when assessing the microcirculation.

We present an inverse Monte Carlo method using a multilayered tissue model for analyzing both diffuse reflectance spectroscopy (DRS) and laser Doppler flowmetry (LDF) data. The output from the model is an assessment of the RBC tissue fraction in mass percentage (%) and their oxygenation in (%), together with perfusion in absolute units (% RBC x mm/s) resolved in three speed regions (0-1, 1-10 and above 10 mm/s).

II. Method

The model of the skin in the wavelength range of 450 to 850 nm consisted of three layers; one epidermis layer with variable thickness and two dermis layers where the upper dermis layer had a fixed thickness of 0.5 mm and the lower had an infinite thickness. The epidermis layer was bloodless while the two dermis layers had different amount of blood with variable speed and equal oxygen saturation. The scattering and absorption properties in the model were described by ten parameters [1], including compensation for the vessel-packaging effect [2, 3]. The three-layer model and the ten parameters are a further development of the model described in [4]. The blood in the dermis layers had a speed distribution that was given by ten parameters. In total the model consisted of 20 parameters (1 epidermal thickness, 1 melanin exponent, 1 melanin fraction, 3 scattering parameters, 2 blood tissue fractions, 1 oxygen saturation, 1 mean vessel diameter and 10 speeds).

By finding a model that fits both DRS and LDF spectra, the inverse problem is solved and the 20 parameters are obtained. This is done in a non-linear optimization algorithm where simulated data are fitted to measured data, initially for DRS and then for LDF. Included in the error function are the intensity difference between simulated and measured data, with an emphasis of wavelengths in the hemoglobin absorption peak region (520 to 600 nm). The error function also penalize non physiological values on the parameters and deviations from unity on the intensity relaxation factor [5].

Measurements were done on one healthy male, age 32, with Caucasian skin. A 5 minutes venous occlusion of the forearm was conducted where the fiber-optic probe was placed in a probe holder and placed on the volar side of the lower forearm. The occlusion preceded by a 5 minutes baseline phase and followed by a 5 minutes reperfusion phase.

DRS spectra were collected at two detector distances (0.4 and 1.2 mm) from a broadband white light source (AvaLight-HAL-S, Avantes BV, The Netherlands) by a multi-channel spectroscope (AvaSpec 2048-5 RM, Avantes BV, The Netherlands). LDF spectra were collected from six detecting fibers placed 1.2 mm from a laser light source (780 nm) and connected to a single detector in a modified Periflux 5000 system (Perimed AB, Järfälla, Sweden).

Calibration of DRS spectra was done in three steps; dark subtraction, white normalization and relative calibration between the two channels, according to Fredriksson et al [4].

III. RESULTS

The RBC tissue fraction, the oxygen saturation and the speed resolved perfusion during the venous occlusion are depicted as a function of time in Fig. 1. The occlusion started at 5 minutes and lasted for another 5 minutes. The oxygenation drops during the venous occlusion while the RBC tissue fraction increases. The drop in total perfusion during the occlusion is caused by the decrease in perfusion for velocities above 10 mm/s and between 1 and 10 mm/s. The perfusion for speed below 1 mm/s is unaffected during occlusion.

The average relative root mean square (RMS) error of the spectral fit for the two DRS distances were 1.0 % for the 0.4 mm distance and 3.7 % for the 1.2 mm distance. For the LDF spectrum the average RMS was 4.7 % (in the logarithmic scale). An example of the fitting for the two DRS channels is given in Fig. 2. The fitting for the one LDF channel is given in Fig. 3.

IV. DISCUSSION

By integrating DRS and LDF not only in the same probe, but also in the model and the spectral fitting gives new opportunities. The fitting of the LDF spectra benefits from the DRS spectral fitting which gives a more accurate estimation of tissue scattering and the vessel packaging effect.

The adaptive three-layered tissue model is fast enough for real-time analysis which gives opportunities to monitor changes in RBC tissue fraction, oxygenation and perfusion while it happens, instead of having to do the analysis afterwards. Also, doing LDF and DRS measurements in the same vascular bed gives new opportunities to interpret data when having more information on the vascular status.

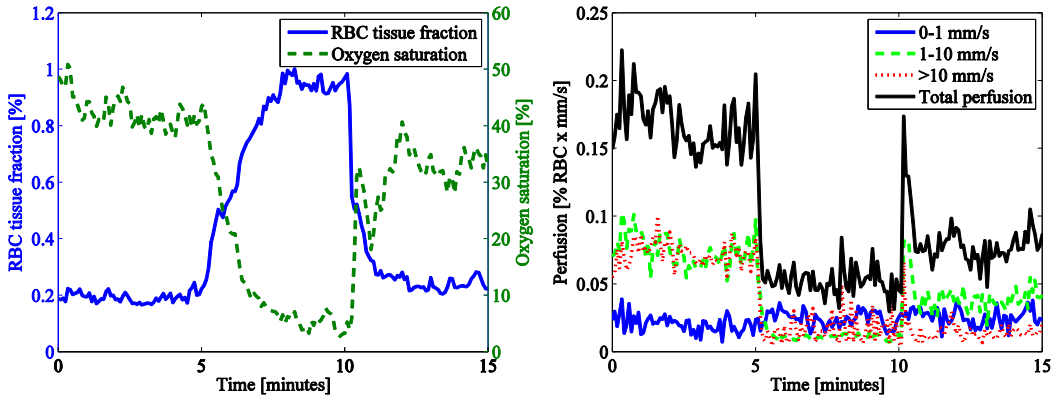

Fig. 1. Time-resolved RBC tissue fraction and oxygenation during venous occlusion (left) and speed resolved perfusion (right).

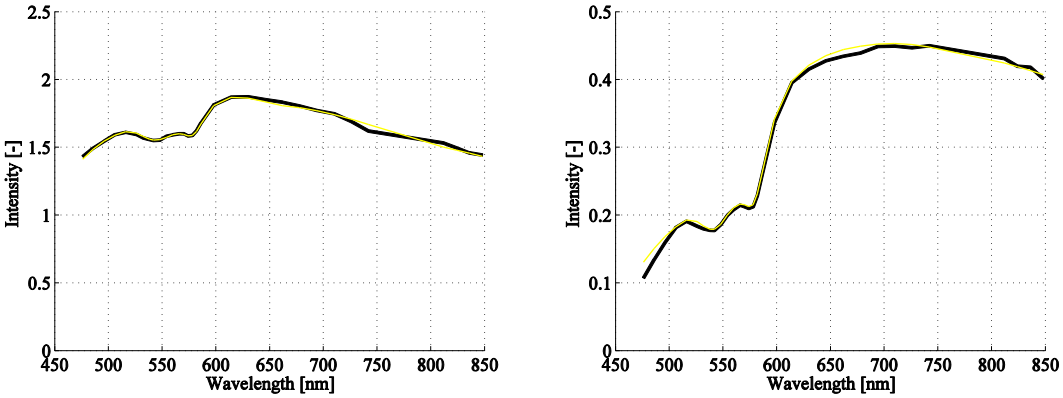

Fig. 2. An example of spectral fit of the DRS spectra at 0.4 mm (left) and 1.2 mm (right) at the beginning of the measurement (black: measured, yellow: fitted).

The oxygenation, the RBC tissue fraction and the perfusion shows expected values during venous occlusion. There is an increase in RBC volume fraction while the perfusion is reduced. This is an indication of the accuracy of the method. Other measurements with provocations like local heating and systolic occlusions have been performed (not presented in this abstract) and shows the same expected results.

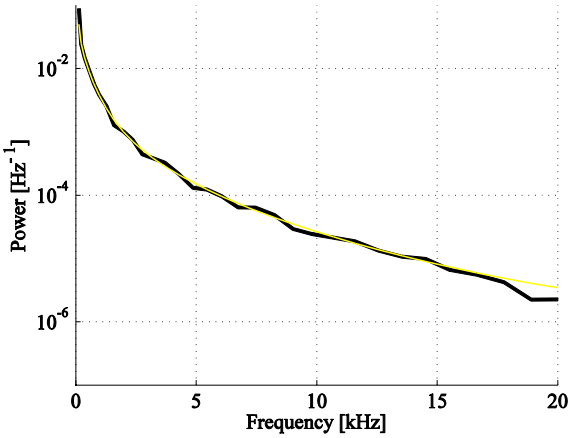

Fig. 3. An example of spectral fit for the LDF spectra at the beginning of the measurement (black: measured, yellow: fitted).

V. CONCLUSIONS

We have presented a combined inverse tissue model for analyzing DRS and LDF data. The model displayed a good spectral fit for both DRS and LDF while being capable of estimating physiological parameters in absolute units. Applied to tissue, the estimated RBC tissue fraction, oxygenation and speed resolved perfusion displayed an a priori expected behavior during physiological provocations.

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