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Skin-remitted photon path lengths: experimental study

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Abstract: Skin-remitted picosecond laser pulses were detected at four input-output fiber distances in the spectral range 560-800 nm. After deconvolution procedures, distributions and mean values of the remitted photon path lengths in forearm skin were analyzed.

1. Introduction

Knowledge on the skin-remitted photon path lengths (SRPPL) and their distributions at particular spectral intervals is needed for several clinical applications, e.g. reflection pulse oximetry or multispectral imaging-based mapping of chromophores in skin malformations. Theoretical SRPPL estimations were based on analytic considerations of diffusion theory [1] or numerical Monte Carlo model calculations [2,3]. However, real skin structures at specific body locations may not correspond to the model assumptions; clearly, direct measurements of SRPPL distributions and their mean values may provide more reliable data.

The previous experimental studies [3-5] gave sense about the durations and distances of photon travels in the skin structures at fixed wavelengths of picosecond lasers. Recently we initiated kinetic studies to cover a larger spectral interval 520…800 nm using a broadband picosecond laser equipped with a set of interference filters [6,7]. The latest results are reported here. The transfer functions representing photon arrival time distributions after delta-pulse launching into *in-vivo* skin were de-convolved, and the distributions and mean values of SRPPL were determined for a number of spatial-spectral combinations.

2. Experimental Set-up and Data Processing

The measurement system has been described in details previously [6,7]. In brief, a "white" picosecond laser (*Fianium, NKT PHOTONICS, DK*, FWHM ~ 6 ps, repetition rate 20 MHz) was used as a light source emitting in the spectral range 450 - 2000 nm. Specific wavelength bands were selected by couples of identical interference filters with 10 nm half-bandwidth (*Andover Corporation, USA*) – one of them filtered the skin input light while the other was placed in front of a fast photon counting detector (HPM-100-07 with controller DCC-100 and data processing card SPC-150, all *Becker&Hickl GmbH*, DE). The examined spectral range was 560-800 nm with a 40 nm step. Repeatable recordings of optical pulse signals via the input and output fibers (WF-400, *Light Guide Optics Int.*, LV) at variable distances between them (8, 12, 16 and 20 mm) were ensured by a specially designed stable-pressure fiber contact probe. Inner left forearms of 5 volunteers with Fitzpatrick skin photo-types II and III were examined with their written consent under permission of the local Ethics Committee.

Processing of the measured data involved comparing the shapes of skin input and output pulses - $a(t)$ and $b(t)$, respectively. The temporal distribution function $f(t)$ of photon arrivals following infinitely narrow δ-pulse input was found by de-convolution of the integral

$$b(t) = \int_0^t a(t-\tau) f(\tau) d\tau \quad (1).$$

This inverse problem was solved using the *Matlab* software. After restoring $f(t)$, the corresponding distribution of SRPPL was calculated as

$$\phi(s) = f(t) \cdot c/n \quad (2),$$

where c is the speed of light in vacuum and n - the mean refraction index of superficial skin tissues (~1.4 [8]). The photon mean path length values were calculated from these distributions, with further analysis of the obtained spectral and spatial dependencies.

3. Results and Discussion

Fig.1 illustrates the skin input (IRF) and remitted pulse shapes measured from a volunteer forearm at two wavelength bands (centered at 560 nm and 800 nm) and several inter-fiber distances. As expected, the remitted pulses broaden with increased inter-fiber distance due to enhanced scattering; shallower penetration at the green wavelength band did not allow detecting remission signals at distances longer than 12 mm.

The SRPPL distributions at all inter-fiber distance / wavelength combinations were calculated accordingly to (1) and (2). As example, two obtained $f(t)$ distributions at 720 nm and the corresponding mean values of photon arrival times in the forearm skin are presented on Fig.2. Averaged over volunteers dependence of the photon mean path

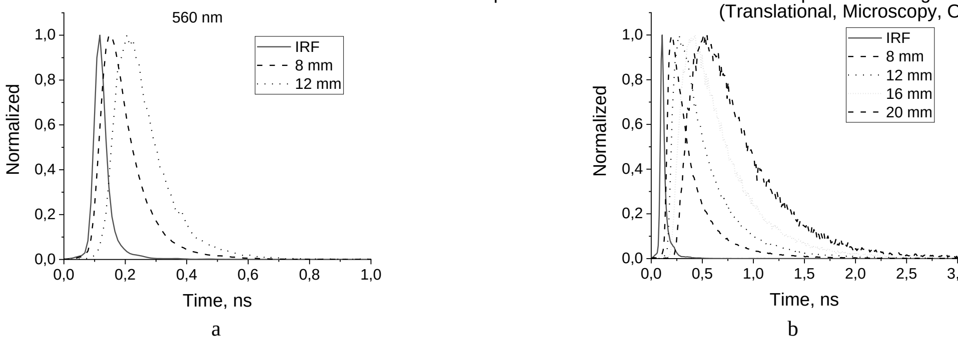

Fig.1. 560 nm (a) and 800 nm (b) input and output pulse shapes at various inter-fiber distances (forearm skin, a single volunteer).

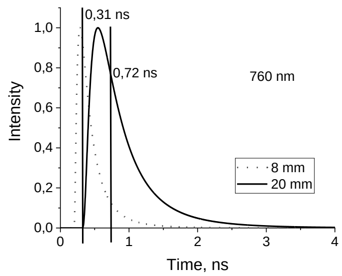

Fig.2. Smoothed distributions of skin-remitted 760 nm photon arrival times and their mean values at two inter-fiber distances.

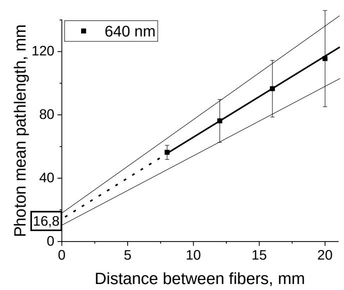

Fig.3. The mean 640 nm photon path length dependence on inter-fiber distance (averaged data).

length on the inter-fiber distance at 640 nm wavelength is illustrated on Fig.3.

The results of this study qualitatively agreed with the theoretical expectations. Concerning the obtained numerical values, they can be regarded as provisional because the remitted pulse signals were extremely weak and noisy, especially in the spectral range below 640 nm. The most reliable data were obtained in the range 680-800 nm at all available inter-fiber distances. Generally, the mean skin-remitted photon path length appear to be 5-6 times longer than the light input-output distance, which agrees well with the previously reported results [3].

From the point of skin diffuse reflectance imaging, the most interesting are spectral dependencies of SRPPL mean values at zero input-output distance. Approximated values were obtained by linear extrapolation of the data recorded at the available inter-fiber distances (Fig.3). However, more accurate measurements by means of contact probes with shorter inter-fiber distances or using the single-fiber approach are to be taken in the future.

4. Acknowledgements

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