Skin-remitted photon path lengths: experimental study

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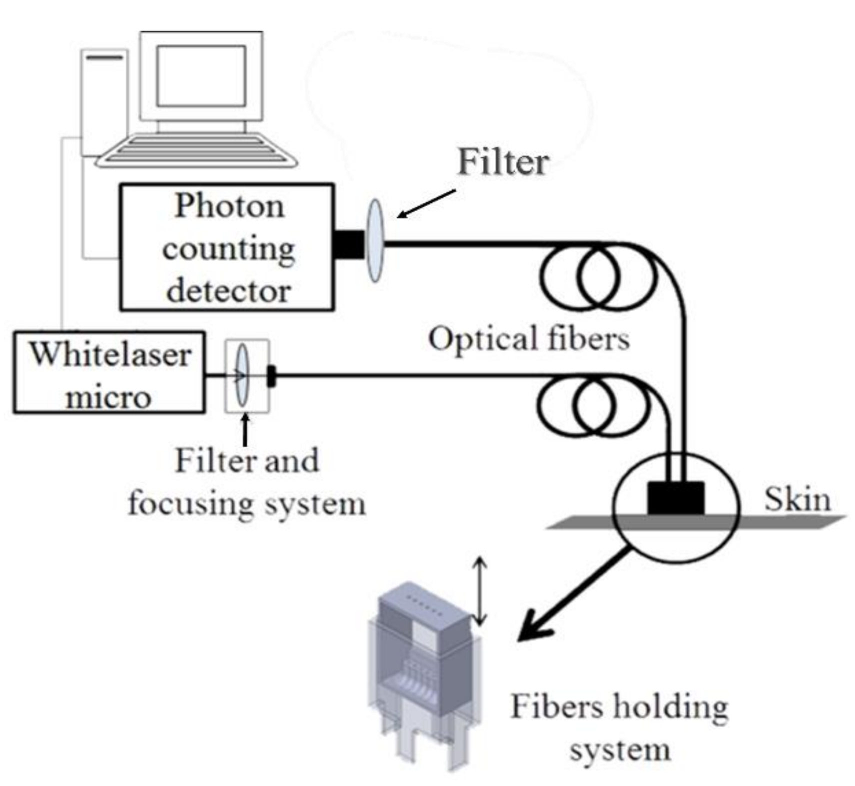
ABSTRACT

In-vivo skin-remitted picosecond laser pulses were detected at 5 input-output fiber distances and 7 spectral bands in the range 560-800 nm. After deconvolution procedures, distributions and mean values of the remitted photon path lengths in forearm skin were obtained along with their spectral and spatial dependencies.

WHY? MOTIVATION:

Skin-remitted radiation is used for optical diagnostics, two examples are reflection pulse oximetry and chromophore mapping in skin malformations. Proper data processing needs the knowledge of remitted photon path length distributions and their mean values at particular wavelengths and input-output distances. Numerical and analytical model estimations exist but have to be complemented by directly measured data that are hardly available.

MEASUREMENT SET-UP



Time-correlated single photon counting method was used for measurements of skin input and output optical pulse shapes. A broadband picosecond laser (*Whitelaser, Fianium, NKT PHOTONICS, DK,* 400...2000 nm, pulse FWHM < 6 ps, repetition rate 20 MHz) was exploited as initial light source. Seven narrow spectral bands of illumination/detection were selected by couples of identical interference filters with 10 nm half-bandwidth (*Andover Corporation, USA*). One of them was filtering the input light while the other was placed in front of the photo-detector - photomultiplier HPM-100-07 combined with the detector controller DCC-100 and data processing card SPC-150 (all *Becker&Hickl GmbH*, DE). The examined spectral range was 560-800 nm, the spectral bands were selected with a 40 nm step. Time resolution of the system was 9.7 ps which ensured minimum detectable photon path length ~2 mm.

Stable recording of optical signals via the input and output fibers (WF-400, *Light Guide Optics Int.*, LV, silica core diameter 400 microns, length 1,05 m) was ensured by means of a custom-made fiber holding probe with fixed inter-fiber distances 1 mm, 8 mm, 12 mm, 16 mm and 20 mm. The probe was designed as a lift where the inside sliding part with the couple of fibers lied on the skin, providing always equal pressure ~ 35 g/cm^2 determined by its weight.

Ten volunteers with skin photo-type II or III (Fitzpatrick classification), age 25... 68 yrs, were examined with their written consent under permission of the local Ethics Committee. The measurements were taken from healthy skin of the forearm, avoiding contact with large superficial blood vessels. The average spectral power density on skin was ~ 10 mW/cm^2.

DATA PROCESSING

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 were found by de-convolution of the integral $b(t) = \int_0^t a(t-\tau) f(\tau) d\tau$ (1). The path length of the first detected photons was obtained as *Min path length = dt · c/n* , where *dt* is the time shift towards output pulse. The inverse problem (1) was solved using a built-in *Matlab* deconvolution algorithm *deconv* , and *f(t)* was calculated. The mean arrival time of skin-scattered photons t_0 was found as a moment when the area under *f(t)* equals from both sides. The mean path lengths of photons in skin were calculated as $f(s) = f(t_0) \cdot c/n$ (2) , where *c* - speed of light in vacuum, *n* - refraction index of skin, ~1.4.

RESULTS

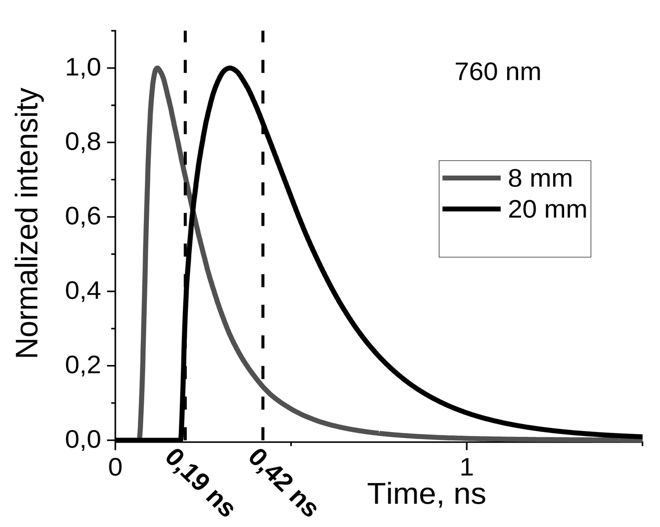


Fig.1. Restored δ-response functions *f(t)*

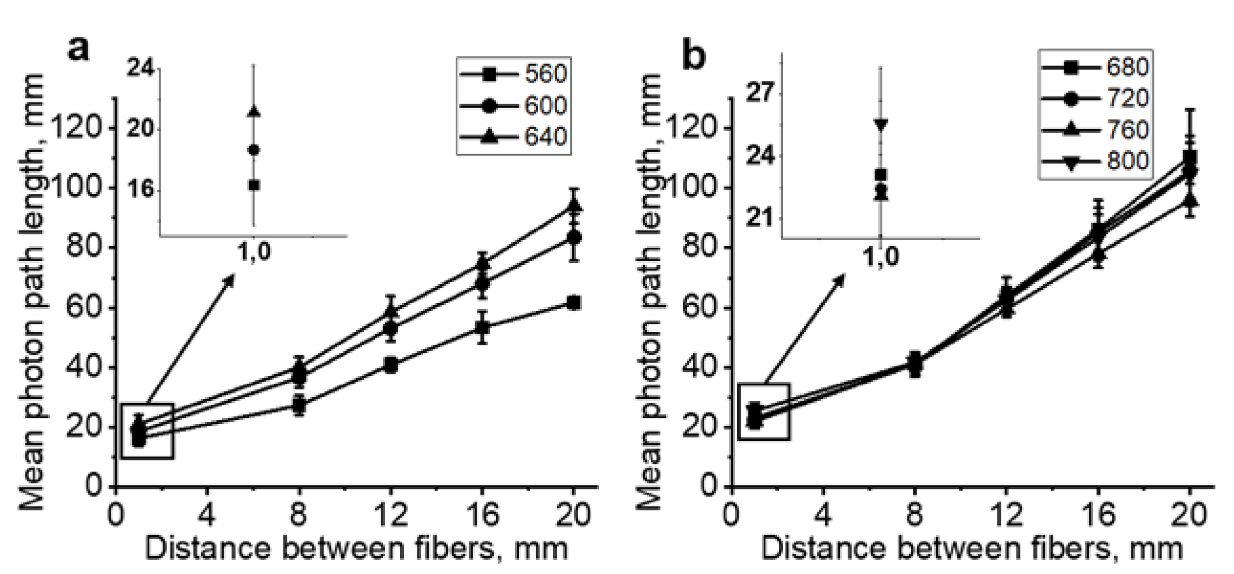


Fig.2. The remitted photon mean path length as function of distance between the input and output fibers.

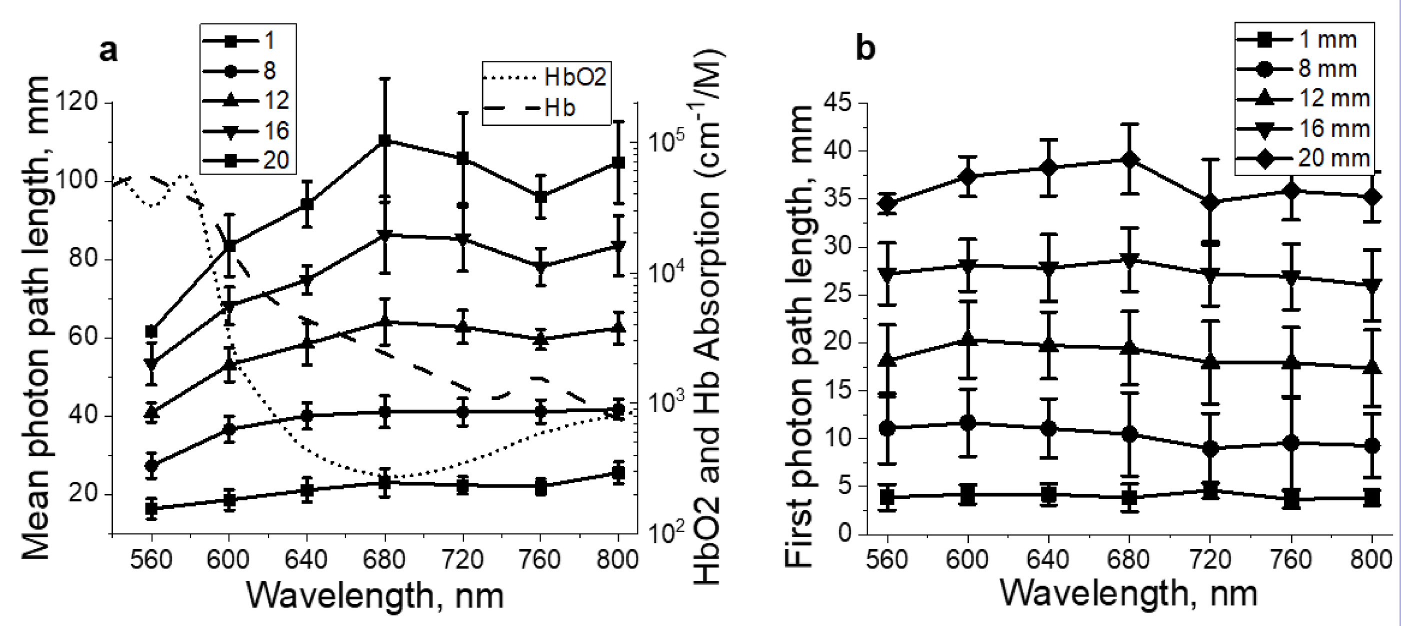


Fig.3. a - spectral dependencies of the mean path length of skin-remitted photons at various inter-fiber distances, b – spectral dependencies for the first detected photons.
Dotted curves: oxy- and deoxy-hemoglobin absorption.

Table 1. The mean skin-remitted photon path lengths (mm, standard deviations) for all spectral-spatial combinations.

Central wavelegth, nm	1 mm	8 mm	12 mm	16 mm	20 mm
560	16 ± 3	27 ± 3	41 ± 2	53 ± 5*	62 ± 1*
600	19 ± 3	37 ± 3	53 ± 4	68 ± 5	84 ± 8
640	21 ± 3	40 ± 3	59 ± 5	75 ± 4	94 ± 6
680	23 ± 4	41 ± 4	64 ± 6	86 ± 10	110 ± 16
720	22 ± 2	41 ± 4	63 ± 4	85 ± 8	106 ± 12
760	22 ± 2	41 ± 3	60 ± 3	78 ± 5	96 ± 5
800	26 ± 3	42 ± 3	63 ± 4	84 ± 8	105 ± 10

*) data of a single volunteer

Table 2. The shortest path lengths of the first detected photons (in mm).

Δx, mm) / λ, nm	560	600	640	680	720	760	800
1	7 ± 3	5 ± 2	7 ± 3	8 ± 4	8 ± 4	7 ± 4	7 ± 4
8	15 ± 13	23 ± 17	26 ± 21	27 ± 24	24 ± 20	23 ± 19	22 ± 18
12	24 ± 15	35 ± 24	40 ± 32	40 ± 30	37 ± 30	36 ± 28	35 ± 28
16	30 ± 18	44 ± 28	52 ± 38	49 ± 37	48 ± 36	47 ± 34	48 ± 35
20	24 ± 17	55 ± 34	62 ± 43	67 ± 47	61 ± 44	58 ± 39	59 ± 42

COMMENTS

The dependencies of photon mean path length on inter-fiber distance (Fig.2) are nearly linear at all seven wavelength bands, R^2 ~ 0.97…0.99.

For the spectral dependencies (Fig.3a), a pronounced maximum around 680-720 nm exhibits, with a following dip at 760 nm. Similar trend was observed for the first detected photons (Fig. 3b).

Possible reason - absorption by the dermal hemoglobin.

SUMMARY

Systematic experimental study enabled obtaining the mean values of the photon path lengths in skin before remission for 35 spectral-spatial combinations, along with the corresponding graphical representations. The spatial and spectral dependencies qualitatively agreed with theoretical expectations while the obtained numerical values were somewhat higher than those obtained by MC-modelling but related to all launched photons.

ACKNOWLEDGEMENTS

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